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INFO-0296

OVERVIEW OF NUCLEAR POWER PLANT EQUIPMENT QUALIFICATION ISSUES AND PRACTICES

by

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A research report prepared for the
Atomic Energy Control Board
Ottawa, Canada

January 1989

Canada

Research report

89-05132/

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A report prepared by K.G. Torr of Monserco Limited, under contract to the Atomic Energy Control Board

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ABSTRACT

This report presents a review of and commentary on the current status of equipment qualification (EQ) in nuclear industries of the major western nations. The introductory chapters discuss the concepts of EQ, the elements of the EQ process and highlight some of the key issues in EQ. A brief review of industry practices and some of the prevalent industrial standards is presented, followed by an overview of current regulatory positions in the USA, France, Germany and Sweden. A summary and commentary on the latest research findings on issues relating to accident simulation, to aging simulation and some special topics related to EQ, has been contributed by Franklin Research Centre of Philadelphia. The last part of the report deals with equipment qualification in Canada and gives recommendations on EQ for new plants as well as currently operational CANDU nuclear power plants.

RÉSUMÉ

Le présent rapport contient une revue et des commentaires sur l'état actuel de la qualification du matériel dans les industries nucléaires des principaux pays occidentaux. Les chapitres d'introduction en présentent les concepts, les éléments du processus et indiquent quelques-uns des problèmes cruciaux. Une brève revue des pratiques de l'industrie et de certaines normes industrielles courantes est suivie d'une revue générale de la réglementation en vigueur aux États-Unis, en France, en Allemagne et en Suède. Le Franklin Research Centre de Philadelphie a fourni un résumé et des commentaires sur les derniers résultats des recherches concernant la simulation des accidents et du vieillissement, ainsi que quelques sujets spéciaux relatifs à la qualification du matériel. La dernière partie du rapport donne un aperçu de la qualification du matériel au Canada et des recommandations pour les nouvelles centrales nucléaires, ainsi que pour les centrales CANDU déjà en exploitation.

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TABLE OF CONTENTS

ABSTRACT i

A. INTRODUCTION 1
1. Note on Terminology 2

B. EQUIPMENT QUALIFICATION 2
1. Seismic Qualification 5

C. EQ PRACTICES IN INDUSTRY 5
1. Stage 1 - EQ Practices Prior to Initial Operation .. 6
2. Stage 2 - Maintaining Qualification during NPP Operation 11

D. KEY ISSUES IN EQUIPMENT QUALIFICATION 13
1. Issues Concerned with Aging 14
2. Issues Concerned with Accident Simulation 22

E. A BRIEF REVIEW OF INDUSTRY STANDARDS ON QUALIFICATION .. 26
1. The Evolution of the IEEE Industry Standards 26
2. Overview of IEEE-323-83 and IEEE-627-80 30
3. Comparison with IEC 780-84 32

F. REVIEW OF REGULATORY POSITIONS 34
1. United States of America 34
2. France 41
3. West Germany 48
4. Sweden 51

G. A SUMMARY OF LATEST RESEARCH FINDINGS 54
1. Background 54
2. Summary and Commentary by Franklin Research Centre . 55

H. EQUIPMENT QUALIFICATION IN CANADA 66
1. Present Status 64
2. Recommendations for New (future) CANDU NPP's 71
3. Recommendations for Currently Operational CANDU NPP's 75

I. RECOMMENDED FOLLOW-UP WORK 75

REFERENCES 77

BIBLIOGRAPHY 78

A. INTRODUCTION

From the earliest days of commercial nuclear power, the fundamental safety objective has been to ensure that the likelihood of a serious release of fission products from the fuel is negligibly small. To this end, care is taken in the design, fabrication and operation of the various process systems to ensure that the fuel's fission energy will be utilized safely and reliably. It is recognized that random failures, while undesirable, cannot be avoided completely, however the consequences of their occurrence is minimized by building in redundant and diverse protective systems for performing the basic safety functions necessary to prevent the accidental release of radioactivity - namely shutdown the reactor, remove the residual and decay heat, and maintain a secure containment envelope. The monitoring of basic plant parameters is an integral part of executing these safety functions.

In addition to redundancy and diversification measures, it is clearly necessary to also provide reasonable assurance that the essential components of the special safety systems and all other systems that contribute towards the execution of the safety functions, can perform their specified safety roles without experiencing design, manufacturing, installation and age-related common cause failures. This amounts to verifying the design of all such equipment by somehow demonstrating its performance capability under significant environmental stresses resulting from the design basis accident conditions, taking into account too, the functional degradation that occurs in service. The business of assessing, monitoring and maintaining the required capabilities of all safety-related equipment is commonly referred to as 'equipment qualification' (EQ).

While the necessity for qualifying all equipment needed to perform the basic safety functions has never been questioned, for this has been consistent with the aims of the advocated safety and quality assurance objectives, the methodology of the qualification procedure has been controversial, and in some respects, continues to be so. There remains, after many years of research and plant operating experience, some unresolved issues, mostly generic in nature, concerning the methods for simulating the accident conditions and the aging of equipment. These issues have been of increasing concern to regulatory bodies, utilities and research organizations.

This report addresses the broad topic of equipment qualification in nuclear power plants. The purpose of the document is to assist the Atomic Energy Control Board staff in developing a technical basis for reviewing equipment qualification programmes in Canada. To that end, the report sets out to present an overview of current practices in four advanced nuclear power countries (the U.S.A., France, Germany and Sweden). The review

broadly covers current regulatory requirements, industry standards and practices in these countries, and briefly summarizes recent research results pertaining to EQ. As this report is aimed at a broad group of readers within the AECB regulatory staff, some of whom may not be familiar with all of the concepts and terminology of equipment qualification, a chapter has been included in this review wherein the key issues are introduced and briefly discussed.

A second objective of the report is to review the status of EQ in Canada, and in the light of the foregoing review, to recommend EQ requirements and standards for application to present and future domestic CANDU nuclear power plants.

1. Note On Terminology

In discussing the various issues on equipment qualification, it is convenient, as in other special topics, to use technical terminology to some degree. Although much of the terminology has originated in the U.S.A., it is now used universally without difficulty in EQ parlance. There are some associated terms pertaining more to the wider topic of nuclear safety, but are necessary adjuncts in EQ terminology - like design basis event, and design basis accident. Much of the material referenced in preparing this report has been American, but some care has been taken to avoid adopting their terminology where it is not interchangeable with Canadian terminology, and longer phraseology has been used instead. However, some American terminology may appear in places for convenience, and while this is not ideal, it would be quite wrong if the reader should infer that such usage in any way implies that the American regulatory approach to equipment qualification is being proposed.

B. EQUIPMENT QUALIFICATION

In its most general context, the term 'equipment qualification' refers to a multi-disciplinary process that starts at the design concept stage of a nuclear generating station, and continues throughout the plant operating life until it is decommissioned.

The overall aim of the EQ process is to provide the most reasonable assurance that the basic safety functions will always be executable. The various postulated initiating events identified in the safety analysis and the assessed plant response to those events, define which systems and components need be qualified, their roles (i.e. both function and mission time) that must be assured by qualification, and also the service conditions under which those roles must be performed. By following a comprehensive EQ programme during the design,

procurement, manufacturing and installation phases, assurance is initially provided that each identified item of equipment will be capable of performing as required under the anticipated service conditions. By continued application of EQ measures, throughout the operating lifetime of the plant, the preservation of those performance capabilities is reasonably assured.

The EQ process centres around comprehensive documentation. Initial specification of performance requirements and subsequent recording of equipment condition forms the basis from which all actions are determined to establish and maintain functional capability. Thus the EQ process is often defined as the generation and maintenance of evidence that supports the assurance of the specified design capability. From the licencing or regulatory organization's perspective, this is the principal means of auditing the requirements, test conditions and procedures for qualification testing at the design stage; and also the principle means of monitoring the qualification status throughout the plant life. From the utility's perspective proper documentation and record keeping is essential to ensure that all factors and components have been covered, and also to formulate maintenance programmes that keep abreast with the changing condition of system components as they age, and need to be replaced, modified, or up-graded.

One of the initial and essential parts of the EQ process is performance verification, normally done by testing the equipment under simulated service conditions, but can also be done by applying mathematical or other logical reasoning. In most countries to date, EQ programmes have focussed primarily on verifying the performance capabilities of electrical components (e.g. cable, sensors, transmitters, electronics, etc.,) and electro-mechanical components (e.g. motors, valve operators, relays, switches, etc.,). Only in some of the new plants in the U.S.A. is mechanical equipment (relief valves, penetrations, diesel motors, etc.,) being looked at, and even then the focus seems to be only upon the organic materials used in that equipment (e.g. gaskets, seals, covers, lubricants). Qualification of such equipment is being done by 'evaluation' of these materials, and not by full testing programmes. A comprehensive EQ programme should cover all equipment types and pay particular attention to the interfaces between these equipment items and their various electrical supplies and control circuits (e.g. connectors, conduit seals, etc.,).

Over the past decade, usage of the term equipment qualification in industry standards and regulatory documentation has been inconsistent in that it has been applied both in a general sense to describe the entire assurance programme, as well as in a more limited sense to the performance verification activities in the first stages of the plan. The complexities in the performance verification part of the qualification process have been the

main focus of attention over the years, and this is possibly the reason for the term being used more frequently in the limited sense. It may have mislead some people to believe that EQ is confined to the initial validation of the equipment's safety performance capability under simulated accident conditions. This is unfortunate, for while this first stage is both necessary and desirable, it is only the first part of what must be a continuous process of ensuring that that performance capability is maintained as the plant ages, undergoes minor modifications, repairs and refurbishment, and experiences various off-normal operating conditions. It is important to perceive EQ as an overall on-going safety assurance programme.

In the text of this report the term equipment qualification is also used in both senses, but an attempt has been made to differentiate between the broad and the specific meanings by using the distinguishing terminology "EQ Process" and "EQ Programme". When the entire assurance programme from concept to decommissioning - including design, initial qualification, maintenance, periodic testing and surveillance - is intended, and is applied to all types of equipment, the term "EQ Process" is used. The term "EQ Programme" has been used to refer to an equipment- and plant-specific programme that includes all aspects of the EQ Process. With these terms being so similar, there is admittedly the potential for confusion, but having not been able to devise better terminology, this convention has been adopted and an effort has been made to write unambiguously.

There are a few other aspects of qualification that are sometimes misinterpreted. The EQ process is not merely a part of normal production quality control testing. It does not yield statistical reliability data, as it is generally performed only once on a single, or at most only a few items of equipment. Reliability should not be confused with qualification. Reliability is the probability that a system performs a specified function or mission under given conditions for a prescribed time; whereas qualification is the generation and maintenance of proof that equipment can operate under all expected service conditions after having operated for a period equal to its expected life.

The EQ process need be applied only to those systems credited with performing a role in the safety analysis of a nuclear plant. Although this might include equipment inside and outside of containment, EQ is chiefly concerned with equipment that must operate in severe conditions (normal operating, accident and post-accident conditions). Therefore identified equipment outside containment is normally limited to that potentially affected by the rupture of pipelines containing high energy fluids.

1. Seismic Qualification

An earthquake is the main event by which significant common cause failures can occur under normal environmental conditions. Other less important events include natural phenomena like external flood, tornado, fire, etc. A comprehensive EQ programme includes seismic qualification, which can also be accomplished by testing, analysis or combined analysis and testing. As a general rule, equipment components required to maintain specific functional capabilities during and/or after an earthquake (e.g. motors, valves and valve operators, electronic instrumentation, etc.,) are qualified by testing; and larger, complex components (piping systems, building structures, etc.,) are qualified by analysis.

The requirements and test procedures for performing seismic qualification of equipment in CANDU plants are well established within the Canadian nuclear industry - to the extent that they have been compiled in a published CSA standard (CAN3-N289.4-86). This standard represents a consensus within the industry of acceptable technical bases for seismic qualification in Canada. This CSA standard deals primarily with the technical aspects of seismic qualification, but it does recognize that seismic qualification forms part of the overall qualification programme. In the 'Note' appended to section 1.3 of the standard, it states that

> "it is important the qualification programme for a component include consideration of all operational loadings (seismic, environmental, aging, thermal, and mechanical stresses, etc.,) for which the component must demonstrably meet its performance objectives."

The details of the various aspects of seismic qualification will not be addressed specifically in this report.

C. EQ PRACTICES IN INDUSTRY

The preceding sections introduced the concepts and objectives of the EQ process and qualification in the EQ programme. This section contains a brief description of the EQ process currently used by the nuclear industry and includes some discussion on the various aspects of the process.

EQ practices in the nuclear industry have been determined primarily by the level of research knowledge and prevailing regulatory requirements (at least in the U.S.A.). As EQ has evolved over the past two decades, industry practices have also developed. In the course of such development, there has been some extension of EQ measures applied to already operating plants, but generally the EQ process has not been applied

retrospectively. For plants under construction, particularly in the U.S.A., current EQ requirements have been imposed. In the following sections, current industry practices are briefly discussed.

There are many parties involved in the EQ process in the industry including the utility, the plant designer(s), the numerous equipment manufacturers and suppliers, consultants, inspection and testing agents. All of these parties contribute in various ways to the general process, but the ultimate responsibility for EQ rests with the licensee.

The development and implementation of the plant specific EQ programme takes place essentially in two stages. The first stage comprises all activities up to the commencement of normal plant operation, and the second stage covers the maintenance and surveillance activities over the plant lifetime. In the discussion below, the focus is upon the industry practices in the first stage, as the efficacy of the second stage measures hinges to a large extent upon the thoroughness with which the activities in the first stage are performed.

1. Stage 1 - EQ Practices Prior To Initial Operation

The whole basis of the EQ programme for the plant is set up during the design/construction/commissioning phases of the project. The three steps in this stage are to

(1) develop a master list of equipment to be qualified

(2) develop the EQ specifications, and

(3) develop and execute a qualification plan that satisfies the requirements of these EQ specifications.

The output of this stage is the documentation that defines the performance requirements and service conditions of all equipment to be qualified, and the reports that verify these performance demands. It forms the basis for procurement documents, production QA, storage and transportation requirements, and the surveillance/maintenance measures during NPP operation.

1.1 Master List Of Qualified Equipment

Central to the development of the EQ specifications is the generation of a master list of equipment that must be qualified - i.e. equipment items identified as essential to perform a necessary role in the plant safety assessment analyses. Equipment that performs an active function as well as that needed to fulfil passive pressure boundary or containment boundary retention roles is included in this list. Also, equipment whose failure could disable any of the above items due to its nature and proximity is also included in the list. Once the master list is completed, it is strictly controlled by permitting only a few individuals to add or delete items, and by having definite procedures and criteria for doing so. In practice, the composition of the master list can only be finalized after the plant design is frozen and the safety assessments completed, however the next stage of the process can commence before this time.

1.2 EQ Specifications

Development of the EQ specifications for each item on the list involves the identification of the items' design requirements from which the qualification specifications are drawn up. The design requirements pertaining to EQ typically include specification of the following:

(i) A detailed equipment specification, including:
- description of the equipment boundary
- details of mounting arrangement and orientation
- details of interfaces with power, water or air services, instrumentation or other equipment
- quality assurance requirements

(ii) A clear definition of the safety function(s) that the specimen will be required to perform in normal, accident and post accident conditions and the corresponding mission times. The performance requirements derived from these function definitions, are translated into acceptance criteria to be applied in subsequent qualification testing.

(iii) Specification of the operating conditions (loads, cycles, etc.,) and environmental conditions the equipment is expected to experience in normal service and any other non-accident service.

(iv) Definition of the operational and environmental conditions arising from the initiating events selected in the safety analysis. This is a critical part in specifying EQ requirements as unrealistic assumptions or over-conservative approximations of accident conditions can have a major impact on the demands on equipment performance, especially as margin is frequently added in type testing performed in the next phase. (In private conversations with one of the head EQ researchers at Sandia National Laboratories, the importance of defining accident service conditions as realistically and accurately as possible was emphasized repeatedly.)

(v) Specification of pertinent standards, design guides, codes or regulatory requirements that must be met.

An important task in establishing the EQ requirements is the identification of aging degradation mechanisms in equipment. Where this is found to be significant, it is normally eliminated wherever possible by selecting a different material or component, otherwise it is taken into account in the qualification programme.

Development of the EQ specifications normally takes place in the early design phases with input being collected from engineers having responsibility for conceptual safety planning, safety analysis, system design and quality assurance. Responsibility for the actual application of the programme is necessarily assigned to the various system designers, but there is normally a dedicated specialized multi-disciplinary group responsible for reviewing and coordinating the various activities. From an early stage there is usually interaction between this group and the various concerned parties in the plant operating staff to prepare for the implementation of the second stage of the EQ programme - the preservation of qualification.

1.3 Qualification Plan

On completion of the EQ specifications, the development and implementation of a qualification plan follows. A unique plan is formulated for each equipment item on the master list. Each plan sets out the method of qualification to be applied and the manner by which the EQ specifications shall be met. In the words of Standard IEEE-323 (1974), the qualification plan acts as an 'auditable link' between the specifications and the test results - i.e. the plan should provide proof that the verification method adopted was adequate.

There are a few different methods of qualification that may be applied. Qualification by type testing under simulated operational (accident and post-accident) conditions is the preferred and most frequent method, but where size or other practical limitations preclude such type testing, another approach must be adopted. Where a history of similar equipment already having operated successfully in equal or less severe conditions exists, information of its operating experience is used to support qualification claims, provided there is sufficient documentation supporting the service conditions and equipment performance. Another method, used only as a last resort, is qualification by analysis in which a mathematical model describing the performance characteristics of the equipment material(s) under various environmental influences is applied. This method tends to be avoided in the industry due to the inherent difficulty in verifying the models. A compromise approach to address this difficulty is to sometimes apply a combined method of qualification in which testing results, operating experience and some analysis are combined to support the qualification claim. Where equipment is found to have a qualified life less than the planned operating life of the plant, an on-going qualification has been suggested as a solution. By this method, the equipment is tested and evaluated during its qualified life span or identical items are removed at intervals and type tested to determine the amount of qualified life span remaining. This is an expensive approach and tends not to be applied in the industry.

The details of the qualification plan depend upon the method selected. In qualification by testing, the plan specifies all the important elements in the testing programme, like pre-conditioning, the sequence of testing and the recording requirements. Development of the test procedures naturally follows, and test details like accident profile, the post-accident conditions and detailed specification of the acceptance criteria at each stage are clearly defined. In qualification by any other means, a good plan clearly defines the basis upon which the correlations and comparisons will be made, lists all supplemental testing required and shows how the component's ability to perform the required safety function, under both normal and accident conditions, is to be demonstrated.

Several industry standards are available and are generally used as the basis for preparing the test procedures for qualification by testing or analysis. They describe the basic requirements, including general principles, procedures and methods, that when met, will confirm the adequacy of the equipment to perform its designated function. The most commonly used standards are discussed in Section E.

The ultimate determination of qualification rests upon verifying that the EQ requirements have been satisfied and that the tests/analysis do in fact encompass the actual application. The qualification report should provide a documented answer to each of the following questions, for each item on the equipment list:

(a) Have all the specified operating conditions and service requirements been covered by the qualification method?

(b) Were all accidents adequately covered ?

(c) Was in-service degradation considered and adequately accounted for ?

and also qualification data, acceptance criteria, evaluation of test results, etc.,

This should lead to the conclusion that the applied EQ method has demonstrated that the specified safety functions can be performed under normal, accident and post-accident conditions, even if called upon at the end of its installed life. Having done this, it is essential that there be some follow-up action (i.e. in-plant inspection) to verify that the tested equipment matches the installed equipment.

1.4 Storage, Transportation and Installation of Equipment

In the qualification process, potential aging mechanisms due to natural, operational and environmental phenomena should be considered over the entire lifetime of the equipment. It appears, however, that common practice is to focus on the changes due to in-plant service conditions during the operating life of the equipment and to ignore the period before it commences its operating life. - i.e. during storage, transportation and installation prior to commissioning. Generally, this apparent omission is inconsequential for no significant aging degradation usually takes place in the preoperational stage, although it is easy to perceive of conditions or events during this period that could make a significant contribution - e.g. physical damage due to handling, impact, transportation; local overheating of component materials during fabrication or construction; exposure to dirt cleaning solvents, water vapour; etc. If the qualification method of particular equipment shows that special care is required, appropriate control measures should be built into the qualification plan that anticipate potential contributory conditions and take suitable action to minimize

their effects. Typical control measures would be avoiding long-term storage of equipment that ages rapidly, adequate protection of equipment during transportation, storage and construction, etc. There should be some procedure in place to ensure that these special requirements are brought to the notice of key people involved in the whole process form procurement to commissioning.

2. Stage 2 - Maintaining Qualification during NPP Operation

During the operating lifetime, equipment items might be exposed to influences whose single and combined effects cannot be accurately predicted. Depending on their history of application, important influences such as temperature, irradiation, stress, corrosion, hydrogen absorption, vibration and fretting can have significant effects on changing material properties, thereby degrading the state of qualification of the equipment. It is therefore necessary to establish and maintain an in-service inspection programme to monitor qualified equipment for possible deterioration and to judge whether their qualification has been compromised.

Operating equipment requires regular maintenance, testing and/or calibration, normally determined by the vendors' recommendations, the utility's reliability requirements and operating experience. However, these measures are frequently limited in that they aim at preserving warranty guarantees for example, or minimizing plant down time, but are not directed specifically at maintaining qualification. The following is a brief summary of the basic elements of a programme aimed at preserving qualification.

(i) There must be an administrative procedure for ensuring that the specified maintenance, calibration and parts replacement schedules are performed consistently. Parts replacement might range from renewing mechanical and elastomer components that wear, or whose mechanical properties degrade (typically seals, covers, gaskets), to reapplying and/or changing lubricants. There should be a mechanism for assuring compliance with these procedures.

(ii) When equipment failures occur, these should be evaluated in the light of maintaining qualification. Obvious questions need to be addressed in so doing, such as: Was this a random failure? To prevent the reoccurrence, does this require modification to the system, the equipment or the operating/maintenance procedures? Does the qualified life need to be revised?.

(iii) Implement and maintain a surveillance programme to ascertain that the effects of degradation remain insignificant. The surveillance programme should amount to performing regular tests and inspections on equipment with age-sensitive equipment.

Recording the findings in all these subsequent qualification efforts in the document files is a vital ingredient in the second stage of the EQ process.

An effective surveillance programme should be based upon an appreciation of the aging mechanisms and failure modes in that equipment, but this is frequently not fully understood. Where unanticipated degradation is revealed through surveillance, there should be a procedure in place for acting on the feedback.

There is an aspect of inspection and testing that goes beyond surveillance requirements, referred to as condition monitoring. Here the objective is to establish a more complete picture of the equipment condition by continuous or periodic evaluation of critical parameters related to the equipment's functional ability, and attempt, where possible, to develop a facility to predict the equipment's future functional capacity. The capability to forecast future performance in accident conditions is necessary where surveillance and condition monitoring is being used as an alternative to type testing of equipment located in a harsh environment. In practice this approach tends to be avoided due to the difficulty in determining the meaningful measureable parameters and their relationship to the functional degradation of the equipment, and the difficulty in obtaining accurate, repeatable measurements by non-destructive (i.e. both non-disruptive and non-invasive) means. Furthermore, criteria for making decisions on data obtained from condition monitoring are at best tentative, but mostly non-existant.

However, in spite of the technological and data limitations, condition monitoring is being applied on a selective basis to equipment (mostly electrical) for which advance warning of impending failure is critical for safety and economic reasons (Ref. 2). A recent example of this approach being developed for application in the industry is the in-situ testing of electrical circuits using a computerized ECCAD (Electrical Circuit Characterization and Diagnostic) system (Ref. 3), developed at TMI-2. This system has also been used at Shippingport NGS and at the Oconee plants by Duke Power. It amounts to measuring the DC resistance and AC impedance characteristics of an electrical circuit, including all cable and connections from the control cabinet to the end device, so that the functional condition of the circuit can be assessed. The characteristics of the circuit are then monitored over time and from this data it is expected that the incidence age-related degradation caused by the plant

environment can be detected and some assessment of the remaining service life might be made. More examples of advancements in research and applications in this field were presented at a recent (1986) ANS/ENS topical meeting (Ref. 4).

When items of qualified equipment need to be replaced, they should be exchanged with qualified equipment. Where identical equipment is either unavailable or undesirable, then the qualification of the replacement equipment must be scrutinized. The U.S. NRC's policy on qualification requirements for non-identical replacement equipment is that it should be qualified in accordance with current EQ provisions, unless there are sound reasons to the contrary. The reasons basically hinge on economic considerations, which briefly are as follows: the item to be replaced is a component that is routinely changed during normal maintenance; or it is only part of a qualified assembly; or the item has been in the licensee's stock prior to an agreed date; or a replacement that complies with current EQ requirements does not exist; or a replacement by new equipment qualified in accordance with current EQ requirements is unavailable within installation and operation schedules, or it would require major plant modifications to accommodate its use. In addition, the replacement equipment qualified to current requirements should not have a significant probability of creating human factor problems that would have a negative impact on plant safety and performance.

D. KEY ISSUES IN EQUIPMENT QUALIFICATION

There are a great number of issues in the broad topic of equipment qualification that demand both clear understanding and careful thought for the proper implementation and regulation of the EQ process. These issues fall roughly into two groups corresponding to the two basic aims of the EQ process:

(1) Issues concerned with the estimation or simulation of the cumulative damage arising from long-term exposure to normal service conditions - i.e. aging degradation; and

(2) Issues pertaining to the simulation of accident conditions and the performance verification of equipment under those conditions.

Due to their number and complexity it is not feasible to address each of these issues in this report. However, a few important concepts inherent in some of the key issues from each of these two groups deserve special attention and are discussed briefly below. The primary purpose of the discussions in this chapter is to provide some background knowledge to the reader who does

not have a detailed understanding of current EQ practices, so that the subjects addressed in subsequent chapters may be better appreciated. In so doing, it is also intended to promote awareness of a few important concepts that are inherent in comprehensive present-day EQ programmes, but have not been applied rigorously or consistently in equipment qualification efforts in operating Canadian nuclear power plants to date.

In a later chapter dealing with current research findings, these topics are expanded upon so that the reader will be able to gain an appreciation of their current status within present-day EQ programmes.

1. Issues Concerned with Aging

Aging of equipment begins after initial manufacture and continues until the end of its service life. It is manifested by permanent physical and chemical changes in the equipment's various constituent materials. The aging mechanisms normally of greatest concern in EQ are those that degrade the organic materials used in electrical insulation, sealing, lubrication and protection of equipment components, but also important are aging effects in inorganic materials by mechanisms such as fatigue, creep, corrosion and mechanical wear. The level and type of environmental conditions (particularly temperature and gamma-radiation) mainly determine the rate of material aging, although the service loading conditions exert a major influence too. While the occurrence of a major design basis accident would result in more severe service conditions, and therefore a greater rate of aging, accident conditions are generally not included in aging considerations, except for radiation doses.

The principal concern is with aging effects that occur during the equipment's long-term exposure to normal and abnormal (transient) service conditions, and that gradually degrade the performance capability of equipment to the extent that it would not function as required under the severe stress conditions that follow a design basis accident. Aging thus increases the potential to cause simultaneous common-mode failures, thereby neutralizing the benefit of redundancy and diversity of safety system design.

This is aggravated by the fact that degradation by aging can be quite insidious and may not necessarily show up in conventional tests under normal operating conditions. For example, conventional megger tests on cable insulation under normal plant conditions will give no warning of cracking due to aging until an advanced level of deterioration is reached, but insulation failure under abnormal wet or humid conditions would occur long before that advanced level of deterioration is reached.

The impact of aging on EQ is that performance verifications on new equipment under design basis conditions at the beginning of its service life, may not provide the desired assurance that those capabilities will be maintained throughout its lifetime. Therefore an essential part of the EQ process should be to assess whether aging has a significant effect on the operability of the equipment. However, the assessment of equipment degradation due to aging remains one of the most difficult areas of equipment qualification. It might better be described as an art, rather than a science, for the aging process is complex and not amenable to the establishment of formal rules, and therefore does not readily lend itself to quantifiable analysis.

There are many in-service stresses that can contribute to aging. These originate not only from external sources due to the ambient environment, but also from internal or operational stresses that are inherent to the functioning of the component. In addition, there are contributory factors that arise from human involvement. Table 1 lists examples of these various stresses. The most common imposed stresses are temperature, nuclear radiation, relative humidity and vibration. In some special cases, there might be additional stresses due to unusual atmospheric conditions like dust, salt spray or oxidizing vapours, or large changes in the atmospheric pressure. While identifying the relevant stresses may be quite straightforward, it is more difficult to acquire accurate and detailed data that describes the variation in intensity of these stresses on the components while in service.

Each item of equipment requiring qualification should be carefully scrutinized for aging mechanisms. Research programmes, accumulated operating experience and knowledge of the equipment and constituent material(s) provides the basis for this examination. Once identified, a judgement as to the <u>significance</u> of the mechanism(s) has then to be made. Some assistance is offered in IEEE-627-80 by way of four general criteria, all of which must be satisfied for the aging mechanism to be considered significant:

- it promotes the same failure mode under normal service environments as occurs due to exposure to abnormal or accident service conditions
- it adversely affects equipment's ability to perform the specified safety function
- the deterioration caused by the aging mechanism is not amenable to assessment by surveillance that provide confidence in the equipment's capability to perform as required in the intervals between surveillance
- it causes appreciable degradation during its design life, comparable to its degradation caused by the design basis events

TABLE 1: AGING STRESSES

1) Internal or Operational Stresses

- Electrical
  - current
  - voltage
- Self Heating
  - electrical
  - functional
- Mechanical
  - self-induced vibration
  - wear

2) External Stresses

- Thermal (ambient, conductive and radiant from process lines and other systems)
- Pressure (ambient room)
- Radiation (gamma, beta*)
- Shock and Vibration
- Chemical (humidity, oxidation, contamination)

3) Other Contributing Factors (Human Factors)

- Maintenance/Repair
- Calibration
- Surveillance
- Testing

* There are other sources of radiation like neutrons, electromagnetic, RF, UV, but these are not included in any known qualification programme.

Where significant aging mechanisms exist, they should be taken into account in the EQ programme, or alternative materials used. Where this is not possible, or the efficacy of simulating the aging mechanisms is uncertain, a replacement programme should be in place to limit aging effects, combined, if possible, with a surveillance programme by which the state of material degradation due to aging is monitored. Through an effective preventative maintenance and monitoring programme, it may be possible to operate the equipment for longer than its qualified life.

1.1 Qualified Life

If the effect of aging is visualized as 'using up' the excess capacity of qualified equipment to withstand the more severe operating conditions during and following an accident, then the time up to the point that the excess capacity becomes zero, corresponds to the qualified life of the equipment. At the end of the qualified life, the minimum functional end point is reached - that is, the equipment would continue to function as required under normal operating conditions, but it would have only enough reserve of functional capability to permit performance of the specified safety function(s) for applicable postulated design basis accident events. Any further degradation beyond the end of qualified life would reduce the equipment's capability to perform as required under design basis accident conditions. This is quite distinct from the "end of life" of the equipment, which is when it fails with no functional capability remaining.

Carfagno in Ref. 5 issues some warnings on the interpretation and application of the qualified life concept. He points out that

> "qualified life established for an equipment item is at best an estimate. A large measure of judgement enters into the analysis. Therefore, qualified life should be recognized as just that: an estimate having major uncertainty. As such it should be subject to periodic review and re-evaluation. It is recommended that the periodic re-evaluation of qualified life be based upon the performance of the equipment in service."

The qualified life is the calendar time that may elapse in normal service before the minimum functional end point is reached. Typically, the qualified life of safety-related equipment ranges from approximately 5 years for devices that degrade rapidly, to 40 years for items whose functional capability can be maintained for the anticipated life of the plant.

In practice, the qualified life is interpreted as the period of normal service simulated by the accelerated aging programme. The period of service following the start of an applicable accident is excluded. Contributions from aging during transportation and storage prior to installation should ideally be taken into account in determining the qualified life, but to date these have not been seriously dealt with due to the environmental conditions during these periods being considered insignificant contributors towards aging effects. One example where this may not be the case is in the common practice of storing electrical cables outdoors where they are exposed to the potentially harmful effects of ultraviolet radiation from the sun, they may be subjected to variations in weather conditions and do not have any special protection barriers from physical damage. Under these conditions, the aging effects might be significant and should be investigated.

The data needed to establish the qualified life of a piece of equipment are listed in Table 2, taken from (Ref. 5).

The qualified life established by a qualification programme thus determines the maximum period that a device may be kept in service with a reasonable assurance that it will perform as required under design basis accident conditions. Routine maintenance, testing and calibration activities are a part of in-service conditions and they, as well as the operational stresses, have a bearing on the qualified life. The qualified life may be dependent on the implementation of scheduled maintenance activities like parts replacement, cleaning, lubrication etc., but they may also have the reverse effect when, for example, errors are made in the procedures.

Typical factors that need to be addressed in a periodic review of the qualified life would include:

(i) any violations in qualification requirements (e.g. inadequate maintenance)
(ii) differences in the severity between the assumed and actual operating history
(iii) any new knowledge that might affect qualification
(iv) any indicated change in status (e.g. increase/decrease qualified life, modify/replace component, modify surveillance/maintenance procedures)

1.2 Simulation of Aging in Type Tests

It is generally assumed that the lowest functional capability of equipment corresponds to its 'end-of-qualified-life' condition, when it has been subjected to the combined effects of a lifetime of stresses. Since it is not practical to naturally age

TABLE 2: DATA NEEDED TO ESTABLISH QUALIFIED LIFE OF EQUIPMENT

DEFINITION OF SAFETY FUNCTION DURING:
- + normal service (including extreme conditions of normal service
- + abnormal service (e.g. during loss of air conditioning system)
- + applicable accidents

DEFINITION OF SERVICE CONDITIONS
- + normal
- + abnormal
- + accident (seismic, main steam line break, loss of coolant)

DEFINITION OF ALL ACTIVITIES THAT CAN AFFECT FUNCTIONAL CAPABILITY
- + maintenance
- + surveillance
- + calibration
- + in-service testing (including testing of other equipment or facilities that affect the functional capability of the equipment being qualified - e.g. reactor building pressure test)

DEFINITION OF TRANSPORTATION CONDITIONS
- + between different geographic locations
- + between different plant locations

STORAGE CONDITIONS (Including Time) AT
- + manufacturing facility
- + supply houses
- + plant site
  - during plant construction
  - after plant starts operation

} Not presently required in U.S.A.

EQUIPMENT CONSTRUCTION DATA
- + degradable materials and components
- + degradable interfaces among materials and components

LIMITING STRESSES OF DEGRADABLE MATERIALS AND COMPONENTS
The limiting values of stresses such as temperature, radiation dose, electric fields, outside of which the degradation of the material or component is not merely faster or slower than it is under normal conditions, but occurs via a totally different process.

EQUIPMENT PERFORMANCE DATA
- + degradation mechanisms
- + failure modes

equipment to the end-of-life condition, techniques have to be adopted to artificially change it to a state equivalent to this condition. Typically, artificial aging techniques aim at component evaluation to be made within approximately 1/100 th of the real in-plant time.

Just how to simulate the actual aging process by aging at this sort of rate presents a major challenge in the qualification test programme. To begin with, realistic ambient plant environments must be known, and the actual environmental effects of the various stresses (radiation, temperature, mechanical, humidity, oxygen, etc.,) must be realistically simulated.

It is most common to account for the individual contributions of the various aging stresses separately in sequential tests, for which there are several generally recommended techniques. For example, the aging effect of thermal and radiation stresses is accelerated by applying the heat and radiation at a greater intensity, and aging due to repetitive operation of the equipment is accelerated by increasing the frequency of the operating cycle. A brief description of the commonly applied techniques are given below.

The current practice of simulating thermal aging is by applying the Arrhenius methodology, which gives the rate of reaction of a material under specified conditions, within a limited range of temperature. A convenient form of the Arrhenius equation for aging calculations is as follows:

$$\frac{t_1}{t_2} = e^{\frac{\emptyset}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)}$$

where

k	= Boltzmann's constant	(eV/°K)
$\emptyset$	= Activation energy	(eV)
t_1	= Qualified life goal	(h)
t_2	= Accelerated thermal aging time	(h)
T_1	= Service Temperature	(°K)
T_2	= Accelerated aging Temperature	(°K)

EPRI has published a good report on the application of this method (Ref. 6). A key factor in this method is the selection of an appropriate value of the activation energy of each degradable material in the equipment item. The lower the activation energy of a material, the greater the degradation in a given period of time at a particular temperature. For an equipment item comprising elements of a number of degradable

materials, each having different activation energies, it would be necessary to remove some of the elements from the equipment item and have them aged separately in order to avoid over/under aging of some of the components. Frequently the "weak link" approach is used where the thermal aging is based on the most susceptible component and other parts are organized to allow the weak link to attain its full age. This approach must, however, be used cautiously.

In radiation aging, it is common practice to subject the item to the total integrated gamma dose the item receives over its qualified life. The presence of oxygen (air) during the simulation can make a great difference to the accelerated aging simulation. One complication is non-homogeneous degradation through the thickness of the sample caused by a limited diffusion rate of oxygen when large thermal or irradiation rates are used. It is possible to minimize this effect by lowering the dose rate or by using thin samples. Work at Sandia (Ref. 4) has lead to the development of quantitative experimental techniques for monitoring heterogeneous degradation effects. These techniques might be suitable for research, but their applicability for EQ is questionable.

Degradation caused by other aging stresses, including cyclic operation, humidity, vibration (non-seismic), and electrical stresses, are more difficult to simulate and are sometimes attempted. Degradation caused by operation of devices is applied most readily to cyclically operated devices (e.g. opening and closing of valves, relay contacts, and starting of electric motors, etc.,) by putting them through a lifetime's worth of cycles in a short period of time. In applying this technique, care needs to be taken to account for the real time effect of environmental conditions during the dwell between operating cycles. For example, relay contacts operated continuously at a high frequency would keep the contact surfaces clean and would not simulate the effect of oxide buildup on infrequently used contacts, which may be a significant contribution to failure.

Although methods of accelerating the effect of humidity have been investigated, there is no practical model of humidity effects suitable for EQ application. Vibration has been given relatively little attention in aging programs due to the difficulty in determining the vibration signature. While the effects of steady electric currents are taken into account through ohmic heating effects and operational cycling, the effect of electric fields have not received much attention. The effect of surges in electrical loading should be adequately accounted for as their effects can be more damaging than steady loading.

2. Issues Concerned with Accident Simulation

Qualification testing for performance verification under design basis accident conditions is normally done by exposing the equipment sequentially to LOCA radiation levels, and then to steam and water at temperatures and pressures representative of anticipated LOCA conditions. Two issues connected with accident simulations are synergistic effects and margins. These concepts are briefly discussed below.

2.1 Synergistic Effects and Sequence of Testing

During the simulation of accident conditions, several environmental factors need to be taken into consideration during qualification - heat, humidity, oxygen, radiation, water spray, steam, vibration, etc. In current EQ practice it is most common to subject the test specimen to these environmental factors partly sequentially and partly simultaneously. For most materials sequential and simultaneous accident simulations produce the same degree of degradation, however synergistic effects have shown up in equipment qualification work on some polymer insulating materials. Generally this effect increases the damage, but in some cases it may decrease total damage. Some examples of of synergistic effects that have been observed are:

- two different materials performing well when tested separately but deteriorating rapidly when combined
  e.g. epoxy seal with cable insulation,
  varnish with magnet wire insulation
- combined heat and radiation altering the rate of cross-linking in a polymer
- oxygen and radiation leading to an enhanced reaction that culminates in permanent scission

As a result of these observations, emphasis has been added to the need for these effects to be considered in performing qualification testing. However the position of expert opinion on the subject goes only so far as to say that caution is advised, but specific advice is scarce. For example, in 1982 the IEEE Working Group 2.6, sub-committee 2, made the following position statement on synergistic aspects of qualification:

> (1) "Existing data bases have been found insufficient to allow general statements to be made relative to performance degradation of safety related equipment resulting from synergistic effects induced by combinations of environmental, process conditions and performance requirements. Therefore, general guidelines of requirements for conducting qualification programs that

include these combinations cannot now be promulgated.

(2) The above does not imply that the absence of synergistic effects is completely unknown, but that synergistic effects that have been identified appear to be greatly influenced by the equipment type and design, tested under certain limited environmental combinations and highly dependent on test methods and procedures. If synergistic effects are present, they might be expected to be of less importance in short-term, real time (i.e. LOCA, Design Basis Accident) testing rather than in long term simulations or under naturally occurring service conditions.

(3) The current licencing atmosphere relative to DBE testing considers the sequential application of service conditions, to the same test specimen, to be an adequate demonstration of the safety function performance capability of an equipment item. Thus, consistent with this position and subject to the limitations previously noted, an awareness of the existence of possible synergisms should be recognized but implementation relegated to research programs strictly for this purpose.

(4) Engineering judgement based upon applicable state-of-the-art information, previous operating experience, and test experience should be considered when evaluating the need for testing under combined environments.

(5) The Working Group recommends that research be conducted that would involve removal of sacrificial samples that were naturally aged and subjected to design basis event testing. By this means industry could monitor its own efforts to determine the importance and existence of synergisms that have been identified.

(6) The Working Group recommends the establishment of data based on specific equipment types as they are qualified and that information be shared so that participants may derive mutual benefit.

(7) The Working Group will continue, as part of its own activities, to monitor the experiences and programs involving suspected synergisms both domestically and internationally and provide assistance in forming a data base to the extent that it can be shared in a timely manner."

The NRC's position on synergistic effects is accordingly low-key, but cautious. In 10CFR50.49 (Jan 21, 1983) synergistic effects is one of the eight factors that must be included in the qualification programme for electric equipment in so far as these "effects must be considered when they are believed to have a significant effect on equipment performance". The NRC has not emphasized the need to look into synergistic effects during the simulation of accidents. If synergistic effects are not identified during preconditioning, it accepts the generally more conservative sequence of radiation aging followed by thermal aging. This approach is consistent with the recommendations given in the latest research summary report NUREG/CR 4301, discussed in Chapter 6.

The most frequently adopted test sequence in the EQ programme is aging (pre-conditioning), then qualification testing which includes radiation exposure (if applicable), vibration (seismic) and finally the LOCA/HELB conditions (temperature, pressure, humidity, spray).

In the large majority of cases this sequence represents the most severe test. However, certain materials improve their mechanical properties when subjected to radiation, so they might be more vulnerable earlier in their lifetime. It might then be more appropriate to perform the vibration testing before, or part way through the aging. Generally there would be more than one material involved and the decision might not be quite so straightforward. In any event, consideration should be given to the testing sequence.

2.2 Margins

An EQ margin is the difference between the most severe conditions specified for a particular component in a plant and the conditions applied in type-testing or analysis of that component. Margins are added to the qualification test conditions to account for

(i) possible variations in products due to manufacturing differences, and

(ii) uncertainties in specifying actual operating conditions for the components being qualified, and inaccuracies in the test equipment.

Margins provides greater assurance that the equipment can indeed perform under the most adverse service conditions specified, by reasoning that if the test specimen performs satisfactorily under 'overtest' conditions, then slightly 'weaker' components should be able to perform acceptably under the actual conditions.

Note that in the EQ sense, margins relate only to the confidence in qualification type-testing, and is unrelated to the other safety margins incorporated in the plant design.

The IEEE and IEC standards recommend that margins be applied to environmental conditions for design basis events, and to extremes of operating conditions. In qualification test programmes, acceptable methods of ensuring that adequate margin does exist include increasing test parameters, number of tests, transients, operability time or test duration - although all these margins need not be put together at the same time. Margins should not be applied to aging parameters. For environmental transients, the standard IEEE-323-83 suggests two alternative ways of applying margins:

(i) by adding margins to temperature and pressure, or

(ii) by applying the peak transient twice without temperature and pressure margin.

As the intent of adding margins is to make the test conditions more severe, the parameters are generally increased, although in some cases a lower value might be more demanding. Thus margins may be positive or negative.

When margins have not been specified, the standard IEEE-323 offers some guidance in selecting appropriate levels by suggesting factors for environmental and power supply parameters. These factors derive from a collective effort by the authors of the standard and from the start were arbitrary, being based upon what the authors "felt" was appropriate. As these factors have no solid technical basis behind them, they should not be applied blindly. However, the tendency, at least in the U.S.A., has been for manufacturers/test laboratories to use only the suggested factors, despite the the fact that the standard recommends that "in all cases, engineering judgement should be used to determine the adequacy". It would appear that the time and effort involved in justifying lower margins are generally not offset by the advantages of less severe test conditions. It is worth noting that standard IEEE-627-80 takes a somewhat different approach to margins by suggesting that "specific equipment qualification standards should provide

specific guidelines on margins" because "it is not practical to specify generally applicable margins" due to the variety of equipment and different demands on the equipment.

In Reg. Guide 1.89 (Rev. 1), the NRC states that the margins set out in IEEE 323-74, except time margins, are acceptable for meeting the requirements of paragraph (e)(8) of 10CFR50.49. In addition, another margin is specified in Reg. Guide 1.89that is not covered in the IEEE-323 standards. The NRC, requiring some assurance of capability of equipment needed only shortly after the occurrence of a postulated initiating event, specifies that all equipment needed within the first 10 hours of the event must remain functional for at least one hour longer than is indicated by the detailed accident analysis (see C.4 in Reg. Guide 1.89). For all other equipment, the 10 % margin on time identified in 6.3.1.5 of IEEE 323-74 is recommended.

E. A BRIEF REVIEW OF INDUSTRY STANDARDS ON QUALIFICATION

The electric power utilities have the ultimate responsibility for qualification, and they have found that carrying out those responsibilities has been both costly and difficult - particularly in the U.S.A. The main reason for the difficulties encountered has been that specific qualification procedures, standards and regulations were evolving at the same time as, or even lagging a few steps behind, the rapid expansion of commercial nuclear power. As most of the western nuclear nations have American-based light water reactors, they have developed equipment qualification policies and procedures in tandem with the American effort. In a general sense, what is now internationally accepted as basic equipment qualification practice - both in terms of published industrial standards and basic regulatory/licencing requirements - has its foundation in the American nuclear industry's experience. It is therefore pertinent to include a brief summary of the history of the development of equipment qualification standards in the U.S.A. in this review paper.

A list of IEEE standards on equipment qualification is presented in Table 3.

1. The Evolution of IEEE Industry Standards

Initially the focus was upon ensuring that the general requirements for electrical equipment were met. Before 1971, qualification measures amounted basically to using high industrial quality electrical components. In the late 1960's some testing of components such as valve operators was begun, mainly to verify their ability to withstand accident conditions.

TABLE 3: TABLE OF IEEE STANDARDS ON EQ

OVERALL QUALIFICATION DOCUMENTS:

IEEE Number	(Reg. Guide)	Subject
IEEE-323-74	(RG 1.89)	Electrical Equipment
IEEE-627-80		Electrical & Mechanical Equipment
IEEE-344-75	(RG 1.100)	Seismic

SPECIFIC EQUIPMENT QUALIFICATION DOCUMENTS:

IEEE Number	(Reg. Guide)	Subject
IEEE-334-74	(RG 1.40)	Motors
IEEE-381-77		Modules
IEEE-382-80		Valve Actuators
IEEE-383-74	(RG 1.131)	Cables
IEEE-649-80		Motor Control Centres
IEEE-650-79		Chargers/Inverters
IEEE-317-76	(RG 1.63)	Penetrations
IEEE-387-77	(RG 1.6,1.9)	Diesels
IEEE-501-78		Relays-Seismic
IEEE-535-79		Batteries
IEEE-634-78	(RS-809-5)	Cable Penetration Fire Stops
P572		Connectors/Connections
P744		Switchgear-Seismic
P638		Transformers
P766		Fire Breaks/Shields - Cables in Raceways
P798		Relays - Qualification
P826		Switchgear

There was no aging and only a short period of post-accident operation was included. These tests were being done while IEEE-323-71 was being developed. After 1971 requirements became increasingly more stringent.

The first industrial standard that addressed equipment qualification was IEEE-279, later withdrawn by the IEEE when more modern standards became available. It is still a licencing basis for many operating American plants. The qualification requirements of IEEE-279 were amplified in IEEE-323-1971. This standard was issued in April 1971 as an IEEE trial-use document and was intended to be a general guide for qualifying Class 1 Electrical equipment. This was the first nuclear-related qualification document.

The updated version of the standard IEEE-323-1974 "Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations" was issued in February 1974 and became the main document pertaining to Class 1E equipment qualification. It provided much more detailed guidance on qualification methodology than the 1971 version. It introduced specific requirements for aging simulations and included suggested factors to be applied to service conditions for type testing to assure adequate margin. It suggested that type tests be run on equipment in a specific order - typically, maximum normal operating conditions, then aging, then seismic simulation, then LOCA simulation. Further guidance was given for aspects of qualification procedures and methods other than type testing, including operating history, mathematical modelling, extrapolation, on-going qualification and modification to the equipment specification during qualification.

This document, although specifically written for Class 1 Electrical equipment, contained a clear presentation of the principles and criteria that are generic to the equipment qualification process itself.

IEEE-323-74 has a 1975 addendum that makes the point that the intent was not for each EQ test to advance the state of art of aging.

In parallel with the development and publication of IEEE-323, several other 'daughter' standards were issued for application to specific electrical components (for example 334-motors, 382-valve operators, 383-cables). The NRC endorsed these standards too, sometimes subject to some modifications, but the detailed criteria contained in them had to be used in conjunction with the more comprehensive criteria of IEEE-323 for evaluating the respective qualification of this equipment.

In 1975, a project was started to produce an overall qualification document applicable to mechanical as well as electrical equipment. This was a joint effort between the IEEE and the ASME with liason members from other institutions. What emerged from this joint effort was a document that had a broadened scope from IEEE-323-74 to cover mechanical equipment, but was not intended to add to or delete from the basic requirements of IEEE-323 as far as electrical equipment was concerned. It benefitted from experience already gained in the production of IEEE-323-74 and included additional details and clarification in several areas:

- qualification requirements
- margins
- specification criteria
- qualification methods
- aging
- interfaces

The document was published in 1980 as IEEE-627-80, but much of the new material intended for it was removed before publication and retained instead for inclusion in the second revision of IEEE-323 that was being prepared at that time.

The current version of IEEE-323 was published in 1983 under the same title as the 1974 version. This latest revision was published to clarify rather than to impose additional requirements for qualifying safety-related electrical equipment. The principal revisions included in the current version are as follows:

- emphasis on the need to establish a qualified life for equipment with significant aging mechanisms, unless aging is adequately addressed by periodic surveillance/maintenance
- more detailed documentation requirements included
- margin requirements relaxed

- explicit statement that margin factors are not meant to be applied to aging

- considerations of mild environments (A mild environment is defined as one expected as a result of normal service conditions and extremes (abnormal) in service conditions where seismic is the only design basis event of consequence.)

- guidance for using equipment operating experience.

2. Overview of IEEE-323-83 and IEEE-627-1980

2.1 IEEE Standard 323-83

IEEE Standard 323-83 describes the basic requirements for qualifying Class 1E equipment (including interfaces). In the brief introduction in Section 4 of the Standard, the necessity of establishing a qualified life for equipment with significant aging mechanisms is emphasized. Section 3 provides a list of key definitions used in the standard, and Section 5 briefly describes four possible methods of qualification. These methods are the means for qualifying equipment, extending qualification and updating qualification if the equipment is modified. Although the intentions and overall principles on this subject are clear, their actual implementation calls for some careful interpretation of terms like 'significant aging', 'adequately taken care of' and 'surveillance actions'.

The core of the document is contained in Section 6 which lays out the various stages in the qualification procedure, and lists pertinent considerations and guidelines inherent in carrying out this procedure.

The foundation of the qualification programme is the development of complete specifications which define the equipment's safety functions and service conditions during which those safety functions are required. The standard lists a number of important items that should be included in the qualification specifications:

- Equipment identification
- Details of interfaces
- Qualified life objective, where applicable
- Safety functions
- Service conditions

From the qualification specifications, the qualification plan is prepared. The fundamental elements of the plan are laid out in the standard, aging being one of the important factors that should be considered. The point is made that the intent should

not be to apply aging preconditioning to all electrical equipment, but rather to address the effect of aging, and deal with it either by testing, analysis or in-service surveillance/maintenance, depending on the equipment design and application. If aging preconditioning is indicated, then the standard recommends that a determination be made as to whether accelerated aging techniques can be meaningfully applied. This involves applying sequentially simulated in-service stresses at magnitudes or rates that are greater than expected in-service levels. IEEE-323 acknowledges that state-of-the-art techniques for simulating aging effects is more advanced for some types of electrical equipment than others, but in all cases the application of established technology should be expected.

Four methods of qualification are described and their basic elements laid out in detail. The four methods are:

Type testing,
Operating experience,
Analysis,
Combination of the above methods

In type testing, it is recommended that margins be applied to the test parameters during qualification testing for design basis event conditions. Where specific guidelines on margins are not given in the equipment specifications, the standard lists a series of suggested factors for guidance. It should be noted that these suggested margin factors are not meant to be applied to aging. IEEE-323 recommends that age conditioning be performed on the basis of conservative estimates of service conditions and conservative accelerated aging techniques.

Section 8 of IEEE-323 sets out a detailed list of recommended documentation for demonstrating that equipment has been adequately qualified. Included in the list are recommended documentation for equipment that operates in a mild environment.

2.2 IEEE-Standard 627-1980

This standard is intended to serve as a general standard for qualification of all types of safety system equipment including mechanical, instrumentation and electrical. It establishes basic principles and procedures to be followed and relies on other guides to provide the details for qualification of specific equipment.

The main body of useful material in the standard is contained in the three Sections 4 through 6, which deals with the fundamental principles of EQ, the criteria to be included in the

qualification programme specification, and the basic steps of the qualification programme itself.

The fundamental requirements for EQ are listed in Section 4 of IEEE-627; namely

(i) Qualification criteria
(ii) Qualification programme to show those criteria can be met
(iii) Evidence of successful completion of the qualification
(iv) A documentation file containing all this information

This section also offers some general guidelines to be applied in considering the three important topics in EQ - aging, qualified life and margins. Four criteria are given to assist in judging whether or not aging is "significant" for the purposes of an aging programme.

The criteria that must be met to qualify an item of equipment form the basis for developing an EQ programme. Ten criteria considered to be included as a minimum are listed and briefly discussed.

In developing a qualification programme, IEEE-627 recommends using a standard test where possible, otherwise a programme should be established by following the following six steps:

(i) Define safety functions
(ii) Review service conditions and establish EQ programme
(iii) Examine previous EQ efforts
(iv) Consider aging and determine best method to account for it
(v) Establish target qualified life
(vi) Develop EQ procedure

Appropriate documentation is needed to verify that the fundamental qualification requirement is satisfied, and that the qualified life is justified. To this end, IEEE-627 lists the basic elements of the recommended documentation files.

3. Comparison with IEC 780-84

Standard 780 of the International Eletrotechnical Commission (IEC) was published in 1984. As the National Committees of fifteen countries, including Canada, U.S.A., West Germany and France, voted in favour of its publication, it represents one consensus on EQ of electrical items in the safety systems of nuclear generating stations. The standard describes the basic EQ requirements including principles, procedures and methods,

that are suitable for both initial qualification and for updating qualification of equipment following modifications.

The IEC-780 standard is laid out in basically the same format as the IEEE-323-83 standard, and is in general consistent with it. The few minor topics on which the two standards differ are highlighted in this section.

In its definitions and the introductory section, standard IEEE-323-83 makes a distinction between 'harsh' and 'mild' environments. In the U.S.A., the concept of 'harsh' and 'mild' was debated extensively, being promoted by the industry to limit the scope of the qualification efforts in severe environments. Only a 'mild' environment is defined in 10CFR50.49, everything else presumably is to be considered 'harsh'. It defines a mild environment as "an environment that would at no time be significantly more severe than the environment that would occur during normal plant operation, including anticipated operational occurrences". The informal NRC guidelines with regard to temperature were:

- Below 135 F (57 C)	Mild Environment
- Between 135 F and 212 F (57 C and 100 C)	Justification of Mild Environment needed
- Above 212 F (100 C)	Harsh Environment

(No corresponding detailed radiation levels were defined by NRC.) In IEEE-323-83, a 'harsh' environment is defined as "an environment expected as the result of the postulated service conditions appropriate for the design basis and post-design basis accidents of the station. (A design basis accident is that subset of design basis events which requires safety function performance.) Harsh environments are the result of a loss of coolant accident/high energy line break inside containment, and post-LOCA or HELB outside containment". The IEC standard makes no distinction between 'harsh'and 'mild' environments, although the general thrust of the fundamental requirements are in agreement with IEEE-323-83.

Both standards accept that qualification may be accomplished in several ways: by type testing, by operating experience and by analysis; or a combination of these three methods. In cases where the qualified life of equipment is less than the anticipated installed life, the IEC document briefly describes how an "on-going" qualification programme may be implemented. This involves either performing accelerated aging tests on identical equipment in parallel with the installation, or naturally aging identical equipment and testing it at intervals less than the qualified life. The same approach was included in the 1974 version of IEEE-323, but was omitted from the 1983 version, apparently due mainly to this being infrequently applied, rather that it being disallowed.

The sections in both standards that describe the recommended test procedures for type testing are almost identical. They highlight the same important aspects that need to be taken into consideration in preparing and executing a test plan. Regarding margins on the test parameters, they both offer the same suggested values that might be applied in the absence of firm specifications. With respect to the application of radiation to simulate degradation from irradiation during operating conditions, the IEEE standard includes an additional condition defining when radiation testing may be excluded. It also states specifically that a gamma radiation source may be used to simulate the expected effects of the radiation environment.

The sections dealing with the procedures for other methods of qualification are essentially the same in both documents. The list of documentation requirements in IEC 780 is similar to that in the IEEE standard, although not quite as detailed.

F. REVIEW OF REGULATORY POSITIONS

1. United States of America

The cornerstone of equipment qualification requirements in the U.S.A. is the group of Nuclear Regulatory Commission (NRC) regulations that specify general safety performance criteria. These are embodied in General Design Criteria 1, 2, 4 and 23 of Title 10, Code of Federal regulations, Part 50 (10 CFR 50), Appendix A, in Appendix B and in 10 CFR 50.55a(h) (Ref. 7). These general criteria are fundamentally consistent with the basic safety criteria implicit in the CANDU safety philosophy, and appear to differ only on that they have been laid out as specific legal requirements. The essence of these general requirements for environmental design and qualification are clarified in NRC's Standard Review Plan (NUREG 0800), section 3.10 and 3.11 (Ref. 8) as follows:

> "Simply stated, the general requirements for environmental design and qualification are as follows:
>
> (1) The equipment shall be designed to have the capability of performing design safety functions under all normal and accident environments
>
> (2) The equipment environmental capability shall be demonstrated by appropriate testing and analyses.
>
> (3) A quality assurance program shall be established and implemented to provide assurance that these requirements are met.

The environmental design of safety-related mechanical and electrical equipment is acceptable when it can be ascertained that all three requirements are met."

1.1 A Brief History of the Evolution of EQ Requirements in The U.S.A.

Over the past two decades, the NRC has used different methods to ensure that the above general requirements were implemented. Several significant documents have been published during this period, each defining EQ requirements at the time. For the uninitiated, reading through this array of documents can present a confusing picture, so a short summary of the history of their development is presented here as an aid to better comprehension.

For plants that were granted construction permits prior to 1971, the NRC accepted the use of high industrial quality electrical components as reasonable EQ provisions. After 1971, the NRC judged EQ measures on the basis of the guidelines of IEEE Standard 323-71. In 1974, the NRC issued Reg. Guide 1.89 'Qualification of Class 1E Equipment for Nuclear Power Plants' - a document which endorsed the updated version of the IEEE Standard 323-74. This guide was used by the NRC staff in evaluating all permit applications for construction of plants after July 1974.

After some pressure from petitions by the Union of Concerned Scientists, the NRC established more definitive criteria for environmental qualification of safety-related electrical equipment in operating stations. This led to the issue of the DOR (Division of Operating Reactors) Guidelines in 1979, which were applicable for the older (pre-1971) plants. Shortly thereafter, the NRC issued a report stating their interim position on EQ (NUREG-0588) which contained two sets of criteria, the first for plants reviewed in accordance with Standard IEEE 323-71, and the second for plants reviewed by the later version Standard IEEE-323-74.

During 1978 and 1979, the NRC issued several Inspection and Enforcement Bulletins that identified qualification problems with various electrical equipment items, including electrical connectors, penetration assemblies, terminal blocks and limit switches. Then in 1980, the NRC elevated the EQ issue to one of primary concern to the American utilities when staff were directed to proceed with making rules on EQ and to have these applied retroactively (backfitting). In the interim, until the rule making was completed, the DOR guidelines and NUREG-0588 were used as the basis for EQ requirements that licensees were to meet.

The NRC's position in its rulemaking activities was intended to promote a policy of upgrading the EQ and reliability of installed electric equipment. The NRC recognized that situations might arise where upgrading may not be feasible or compatible with plant safety, but licencees were instructed to review each situation on an individual basis. Sound reason to the contrary had to be presented before exceptions to this policy were granted.

By 1983, the NRC ammended its regulations regarding EQ of electrical equipment by publication of a final rule 50.49 of 10 CFR 50. In addition Reg. Guide 1.89 was revised to reflect the NRC's latest position on EQ. It describes methods that are acceptable to the NRC for complying with rule 50.49.

1.2 Summary of Rule 50.49

This rule applies to the qualification of three categories of electric equipment important to safety, namely:

(1) Safety-related electric equipment (also described as Class 1E equipment in IEEE Standard 323-74)

(In NRC terminology, safety-related electric equipment is identified as a subset of electric equipment important to safety and defined as equipment that is relied upon to remain functional during and following design basis events to ensure

(1) the integrity of the reactor pressure boundary
(2) the capability to shut down the reactor and maintain it in a safe shutdown condition
(3) the capacity to prevent or mitigate the consequences of accidents that could result in potential offsite exposures comparable to the 10 CFR Part 100 guidelines.)

(2) Non-safety-related equipment whose failure under postulated environmental conditions could prevent the accomplishment of the basic safety functions

(3) Certain post-accident monitoring equipment (Reg. Guide 1.97 offers more specific guidance as to what parameters should be monitored and hence which monitoring equipment should be qualified.)

The rule deals only with qualification in harsh environments, i.e. it excludes qualification requirements for:

(i) seismic and dynamic conditions. (These were covered elsewhere, but not in the Code of Federal Regulations.)

(ii) environments arising from natural phenomena, other than earthquakes that did not affect either the capability to shutdown, the integrity of the reactor pressure coolant boundary, or the capability to mitigate releases of radioactivity by containment.

(iii) safety-related equipment operating in mild environments

The rule specifies several basic elements of the required EQ programme:

(1) A list of equipment important to safety must be prepared. This list must also include the following information:

(a) Performance specifications for both normal and accident conditions
(b) Electrical specifications like voltage, frequency, load, etc., for the above operating conditions
(c) Environmental conditions like temperature, pressure, humidity, radiation, etc., for normal and accident conditions

(2) In the EQ programme, equipment must be qualified for the most severe design basis accident conditions it will experience. The programme must include consideration of the following effects:

Temperature and Pressure
Humidity
Chemical spray
Radiation
Aging
Submergence
Synergism
Margins

Regarding radiation, qualification must be based on the integrated dose expected over the normal operating lifetime, and the radiation associated with accident conditions, and should include consideration of dose-rate effects.

Regarding aging, equipment qualified by testing must be preconditioned by natural or accelerated aging to its end-of-life condition. If this is not practicable, then preconditioning to a shorter designated life is permissible, but the equipment must be replaced or refurbished at the end of this period, unless on-going qualification can demonstrate that the item still has additional life. In considering aging, all relevant, significant types of degradation must be considered.

Margins must be applied to account for uncertainties in production or test measurements. These are in addition to conservatisms included in deriving local environmental conditions, unless these incorporated adequate quantifiable margins.

The acceptable methods of qualification are defined as:

- Testing of identical items under identical conditions, or similar conditions with supporting analysis
- Testing of similar items with supporting analysis
- Experience with identical or similar items under similar conditions plus supporting analysis
- Analysis combined with pertinent type test data that supports assumptions and conclusions

A record of qualification must be maintained in an auditable form for the whole time that each particular item is installed - or is stored for future use. The documentation must verify that the equipment

(i) is qualified for its application, and
(ii) meets with its specified performance requirements under all expected conditions

Finally, equipment that was successfully qualified in accordance with previously acceptable guidelines (DOR guidelines or NUREG-0588) need not be re-qualified, but replacement equipment for these items must be qualified in accordance with these latest requirements.

1.3 Regulatory Guide 1.89 (Rev 1), June 1984

(This version of Reg. Guide 1.89 is due for revision in response to the publication of IEEE-323-83.)

Reg. Guide 1.89 describes a method acceptable to the NRC for complying with the above rule with regard to qualifying safety-related electrical equipment in a harsh environment.

The regulatory position of the NRC is laid out in Section C of the Guide. In general, the NRC accepts the EQ procedures described in IEEE Standard 323-74, subject to a few conditions:

(1) Specification of Performance and Environmental Conditions

Section C 2 lays out specific methods for establishing these specifications. For example, for determining temperature and pressure conditions inside containment following a LOCA or Main Steam Line Break, the guide lists acceptable methods for calculating mass and energy release rates, as well as particular computer codes for calculating containment parameters; and specifies the source terms for determining the post-accident radiation environment.

(2) Type Test Procedures

The several supplementary conditions specified in the guide add a few details to the standard's methods of performing the type tests, e.g. where to measure test parameters relative to the test piece; monitoring of variables that might indicate temporary failure; which gamma sources are acceptable; etc.

(3) Margins

Basically, the margins recommended in IEEE Standard 323-74 are acceptable; otherwise quantified margins need to be applied to the environmental calculations described above. For equipment required within only the first 10 hours into the accident, a one hour margin is specified, unless a shorter time margin can be justified.

(4) Aging

In the discussion section of the Reg. Guide, it is acknowledged that there are considerable uncertainties regarding the aging processes and environmental factors that could result in aging degradation, e.g. oxygen diffusion, humidity, and accumulation of deposits. The existence of such uncertainties means that the state-of-the-art techniques of preconditioning are unable to simulate all significant types of degradation, but advances in the technology leading to improved effectiveness in preconditioning are anticipated.

The Arrhenius methodology is considered an acceptable approach of addressing accelerated thermal aging within the limitation of state-of-the-art technology. The aging acceleration rates, and the activation energies used in the EQ testing programme must, of course, be fully documented, as well as their basis for selection.

To account for the uncertainties regarding age-related degradation, it is suggested that a combination of

(1) preconditioning and
(2) surveillance, testing and maintenance

be considered. Special attention should be paid to those processes that are known to be not readily simulated by preconditioning and that could cause significant common-mode failures. The NRC will accept the output from such programmes as "on-going qualification" to update the qualified life of equipment. This should be incorporated into the maintenance and repair/replacement schedules.

Where synergistic effects have been identified before starting the EQ programme, these must be taken into account. Known synergistic effects are:

(i) the effects of radiation on oxidation and the influence of dose rate, and
(ii) the effects of applying radiation and elevated temperature in different sequences.

As required by rule 50.49, all replacement electric equipment installed subsequent to 22 February 1983, must be qualified to the latest requirements, unless there are sound reasons to the contrary. The Reg. Guide provides a list of sound reasons where replacement of equipment previously qualified to "older" standards, would be acceptable instead of upgrading. These are:

(i) Item is routinely replaced during normal maintenance
(ii) Item is part of a qualified assembly
(iii) Identical equipment was in stock prior to February 1983
(iv) Qualified replacement equipment does not exist
(v) Qualified replacement equipment cannot meet Schedules
(vi) Replacement equipment requires major plant modifications or adversely affects plant safety by causing human factor problems

2. France

In France, EDF, the national electric utility, is required by law to qualify safety-related systems to ensure safe operation under a set of "plausible operating conditions" - i.e. all plant operating conditions up to and including, but not beyond, design basis accidents. The licencing authorities have drafted regulations entitled 'Basic Rules of Safety' for these systems and the conditions for their qualification. The Basic Rules, which cover both mechanical as well as electrical equipment, require all equipment be qualified that performs a safety function (Class 1E equipment) and whose function is deemed necessary for the safety of people or equipment availability. Four qualification procedures have been defined and equipment is qualified in accordance with one of these procedures depending on its location and its specified performance requirements. Briefly, these are:

(1) standard qualification procedure

(2) qualification procedure K3 for equipment outside containment (normal service conditions and seismic)

(3) qualification procedure K2 for equipment inside containment (normal service conditions and seismic)

(4) qualification procedure K1 for equipment inside containment (normal, accident and post-accident conditions and seismic) The first procedure, the standard qualification procedure, applies to all equipment items and forms a necessary part of the qualification process. The other three procedures are specific to each particular category of equipment.

The French equipment qualification requirements are set out in the French National Code, the RCC-E (Regles de Conception et de Construction de materiels Electriques des ilots nucleaires). Table 4 summarizes the French standards applied in qualifying electrical, instrumentation, mechanical equipment and structures. As in the United States, the construction of some of the early 900 MW plants was completed before the final implementation of the national qualification programme. These plants have subsequently been back-fitted to upgrade their qualification status.

The basic rules governing the qualification process are universal: the stated purpose of the qualification process being to demonstrate that the equipment is suitable for the use intended, and that it is not susceptible to failure which would have an adverse impact on safety. The equipment performance

TABLE 4: FRENCH STANDARDS ADOPTED IN THE QUALIFICATION OF ELECTRICAL, MECHANICAL AND INSTRUMENTATION EQUIPMENT FOR 900 MW AND 1120 MW PLANTS

	Environmental		Seismic
	Aging	Accident	Aging & Accident
Electrical & Instrument'n Equipment	RFS IV-1-a RFS IV-2-b RFS V-2-a RFS V-2-d * RCC-E CEI 544	RFS IV-1-a RFS IV-2-b RFS V-1-a RFS V-2-d RFS V-2-f RCC-E CEI 544	RFS I-3-b RFS IV-1-a RFS IV-2-b RFS V-2-d RCC-E UTE C 20-420
Mechanical Equipment	RFS IV-1-a RFS IV-2-a RFS V-2-a * CEI 544 RCC-M	RFS IV-1-a RFS IV-2-a RFS V-2-f CEI 544 NFT 30 900 NFT 30 903 RCC-M	RFS IV-1-a RFS IV-2-a UTE C 20-420 RCC-M

* Up to 10/08/84

requirements for all service conditions must be clearly specified, as well as the methods to be employed in the qualification process and the criteria governing acceptance.

In common with other nations, the French permit qualification by testing, analysis or a combination of both methods. The combined and analytical methods are used primarily to:

(i) maintain equipment qualification when the equipment has undergone major modifications
(ii) identify possible unsafe failures and failure mechanisms
(iii) qualify a series of items of equipment on the basis of one or more qualified models
(iv) qualify equipment when qualification by testing proves impractical, e.g. for reasons of equipment size

The data used to guide or support the proof may be operating experience with similar equipment, partial tests or tests carried out on prototypes.

With regard to unsatisfactory results or equipment failures during qualification testing, the French have adopted what seems now to be a universally accepted (see for example IEEE-323-83, section 6.7) concept: If an analysis of the failure mechanism shows that the equipment failed due to an effect unrelated to the test (e.g. the test equipment malfunctioned, or the equipment was inappropriately tested), then the equipment can be repaired and the testing continued. If however analysis of the failure shows a causative link with the test conditions, the equipment may need to be modified or replaced before proceeding with the qualification testing programme. Only in exceptional cases will it be permissible to consider re-defining the test conditions or failure criteria to qualify the equipment.

2.1 The Standard Qualification Procedure

The purpose of the Standard Qualification Procedure is to ensure that the equipment is capable of performing its specified functions under normal service conditions. This is achieved by carrying out a specific qualification programme peculiar to each type of equipment. Generally the programme consists of a series of tests, comprising

Reference tests,

Performance tests, and

Mechanical proof and/or functional tests.

The conditions and the sequence of these tests are tailored to the particular equipment being qualified.

The Reference tests (performed with equipment in new condition) serve as a reference for subsequent tests and are normally performed under standard atmospheric conditions, with only nominal values of the identified environmental influences. These tests typically measure functional and electrical interface characteristics (e.g. dielectric tests, insulation resistance, etc.,).

The Performance tests serve to verify the functional characteristics of the equipment within, and up to, the limits of the normal range of service conditions. Environmental conditions such as normal pressure, temperature, humidity, etc., would be included, as well as operating conditions specific to each equipment item and related to its condition of installation (e.g. torque, vibration), or to the characteristics of the required energy sources (e.g. electrical interference).

The Mechanical proof and/or functional tests are intended to verify the mechanical strength of the equipment and/or to evaluate its functional characteristics. These may be combined with the Performance tests.

2.2 The Specific Qualification Procedures

As mentioned above, all equipment that performs a safety-related function must be qualified in accordance with qualification procedure K1, K2 or K3.

The Category K3 procedure is tailored for equipment that is installed outside containment and must be capable of performing its required functions only under normal conditions and under seismic loading. Qualification requirements are satisfied by the standard qualification procedure and seismic qualification tests.

The Category K2 procedure is similar except that it is for equipment installed inside containment that must perform its required functions under normal conditions and under seismic

loading. In both the K2 and K3 categories, the seismic tests may be performed on a new specimen, different from that subjected to the standard qualification procedure, provided that this can be justified.

The most extensive qualification procedure is for Category K1, which is for equipment inside containment that must be capable of performing its designated functions under seismic loading and under normal, accident and/or post-accident conditions. The qualification process is a specific programme of tests peculiar to each type of equipment that comprises the following, applied in the same sequence:

(1) Reference and performance tests

(2) Application of stresses corresponding to the normal conditions under which the equipment operates during its period of service, and to seismic loading. These stresses are applied in the form of

- Mechanical proof and functional tests
- Seismic tests

(3) Tests simulating accident conditions

(4) Tests simulating post-accident conditions

In the last two tests, the applied stresses need only be representative of specific conditions to which the equipment is subjected due to its specified functions, and under its actual installation conditions. Margins are however applied on temperature (+10 C), Pressure (+0.5 bar) and total dose of irradiation. These margins are to allow for

- uncertainties in the analysis code calculations,
- different locations of the same equipment within the containment
- synergisms between irradiation and temperature (applied separately)
- equipment characteristic dispersion due to the small number of specimens tested

For the Mechanical proof and functional tests equipment is subjected to the following successive tests:

- thermal aging test
- damp heat test
- prolonged operation test
- irradiation aging test
- vibration aging test

This particular sequence does not always have to be followed, but in all cases, the last four of the above tests must be performed. When it is not possible to perform thermal aging, due say to the test time being too long, then an alternative method must be applied (e.g. temperature cycling, cold, heat, etc.,) which will induce equivalent aging stresses.

2.2.1 Thermal Aging Test

Thermal aging can be performed either by applying a method suitable for the type of equipment to be tested (e.g. Arrhenius Law, Montsinger Law, Ten-degree Law, etc.,), or if such a method has not been developed, thermal aging is to be for 950 hours at 135 C.

2.2.2 Damp Heat Test

This test is performed as specified in Standard NFC 20-504. The 2-cycle method is applied with equipment not energized.

2.2.3 Prolonged Operation Test

This requires a suitable test plan, based upon the particular equipment's service parameters like load conditions, operating mode, number of cycles, ambient temperature, etc. This test is performed at the highest temperature anticipated for normal service conditions.

2.2.4 Irradiation Aging Test

The standard conditions for irradiation aging are as follows:

* Equipment is not energized

* Equipment is kept as a steady temperature of 70 C $\pm$ 3 C

* An air equivalent dose of 250 kGy ± 15 % (25 Mrad) is applied

* The dose rate is 0.28 ± 0.14 Gy/s (0.1 ± 0.05 Mrad/h)

* For electrical penetrations, the dose is 50 kGy (5 Mrad) and the rate is 0.056 ± 0.028 Gy/s (0.02 ±0.01 Mrad/h)

Note that the dose applied in this test accounts only for the integrated life dose that the equipment receives under actual installed conditions.

2.2.5 Vibration Aging Test

Vibration aging is performed over a frequency range of 10 Hz - 500 Hz and follows the Standard NFC 20-516 procedure. The severity level of this test is determined by the equipment's specific operating conditions.

This test is not performed when either the operation of the item itself is the main source of the vibration (e.g. some motors), or when it is not a suitable means of evaluating the equipment's mechanical characteristics (e.g. cables).

2.2.6 Seismic Test

The seismic test verifies the ability of equipment to perform its specified functions when subjected to S2 loading in the UTE Guide (S2 corresponds to the Safe Shutdown Earthquake). The test is preceded by an exploratory test for determining critical frequencies. Seismic testing may be performed on a new specimen different from that subjected to the standard qualification procedure when aging effects are insignificant.

2.3 Accident Environment Simulation

The LOCA conditions are simulated by first subjecting the equipment to an additional "accident radiation dose" and then exposing it to steam and chemical spray.

The accident dose is again carried out with the equipment temperature kept at 70 C ± 3 C. An air equivalent dose of 600 kGy (60 Mrad) is applied at the same rate as before.

Before the LOCA temperature-pressure transient is applied, the equipment is held at a constant temperature of 50 C ± 10 C for 24 hours. An initial temperature-pressure transient is applied which lasts 12 min. A recovery period follows the transient, allowing the specimen to return to a stable temperature of 50 C. The same temperature-pressure profile is applied again, but after 200 seconds the equipment is exposed to a chemical spray lasting 96 hours - i.e. until the end of the test.

2.4 Post-accident Environment Simulation

The standard post-accident test conditions are as follows:

* humidity above 80 %

* absolute pressure 200 kPa ± 50 kPa

* test duration 10 days and temperature 100 C.

3. West Germany

In the Federal Republic of Germany, both construction and operation of all nuclear facilities require a government licence. The statutory bases for these licences are defined by the federal Atomic Energy Act. In common with other western nuclear countries, this law incorporates requirements for ensuring adequate equipment qualification.

In Germany, the licencing of nuclear power plants is controlled by the highest state authorities, who employ the personnel of external reviewing organizations as advisors for preparing analyses, providing expert opinions and for performing on-site examinations. In the majority of cases, the regional Technical Supervisory Agencies [Technishe Uberwachungsvereine (TUVs)] and the Reactor Safety Society (Gesellschaft fur Reaktorsicherheit) are entrusted with these tasks.

The recommended industrial practices to be adopted for compliance with the nuclear regulatory requirements are laid down in standards developed under the auspices of the German

Nuclear Safety Standards Commission [Kerntechnischer Ausschuss (KTA)], as well as the German industrial standards (DIN) and the German electrotechnical standards (VDE). Some of the more important KTA Standards are listed in Table 5. These standards are followed closely in the German nuclear industry, with deviations being permitted only where necessary, and only after approval by the regulatory authorities.

In the 1970's, EQ tests were based on in-house specifications approved by the TUV's, but aging was not applied in all cases. Since the end of the 1970's, KTA Safety Standards such as KTA 3503 (Reactor Protection System, "Mild Environment"), KTA 3504 Valve Actuators, "Harsh Environment") and KTA 3505 (Sensors, Transducers, "Harsh Environment") have replaced these specifications, so that now preconditioning and simulation of post-accident conditions are now obligatory.

The general sequence of the qualification process in Germany is in keeping with internationally accepted practices. Their process starts by identifying all the equipment components that need to be operated and the maximum expected operating conditions for each specific component - i.e. service loads, types of design basis accidents, duration and operability of design basis accidents. The specification documents for the qualification process are then prepared, incorporating the requirements of the KTA, DIN, VDE standards. The German authorities accept qualification by analysis or testing, but type testing is the preferred approach.

Qualification by testing in Germany incorporates the following basic steps:

- Spot check of samples at the manufacturer, to ensure that the equipment is fault free and in compliance with the specifications
- Mechanical and thermal aging
  (e.g.: 500 - 2000 load cycles for valve actuators,
  20000 load cycles for switches,
  Calculations are normally done in accordance with Arrhenius methodology, paying attention to the material threshold temperature to prevent overstressing.
  Typically, thermal aging would be at 135 C for 10 days.)
- Irradiation test to simulate in-service dose. (Typically this is 5 Mrad at 50 krad/h)
- Vibration endurance test (Seismic and non-seismic)
- Demonstration of resistance to temperature, humidity and pressure (LOCA/HELB test)
- Irradiation test to simulate the accident dose. (This is 20 Mrad at 50 krad/h)
- Post-accident environmental and corrosion test - typically 56 days in duration.

TABLE 5: A SELECTION OF GERMAN NUCLEAR SAFETY STANDARDS

KTA 1501 (1977)	Stationary System for Monitoring Local Dose Rates within Nuclear Power Plants
KTA 3403 (1980)	Cable Penetrations through the Reactor Containment
KTA 3501 (1985)	Reactor Protection System and Monitoring Equipment of the Safety System
KTA 3502 (1982)	Incident Instrumentation
KTA 3503 (1982)	Type Testing of Electrical Modules for the Reactor Protection System
KTA 3504 (1984)	Electrical Drives of the Safety System in Nuclear Power Plants
KTA 3505 (1984)	Type Testing of Measuring Transmitters and Transducers of the Reactor Protection System
KTA 3506 (1984)	Tests of Electrotechnical Control Systems of the Safety System of Nuclear Power Plants
KTA 3507 (1982)	Factory Tests of Equipment for Instrumentation and Control

Superheated test profiles are not specified in the German safety standards.

The simulation of post-accident environmental conditions is accelerated by applying Arrhenius methodology, with the air temperature between 70 and 90 C and 100 % relative humidity.

Thermal and irradiation preconditioning on control equipment components such as coaxial cables, transformers, transducers is done in the energized condition according to KTA 3505. Relative humidity for thermal aging is not specified and therefore ambient conditions are applied.

Qualification tests must include all the equipment's interfaces (e.g. connection boxes, splices, terminal boards, electrical connections, grommets, gaskets, cables, conduits, enclosures, etc.,)

4. Sweden

Most of the documentation that specifies the equipment qualification requirements for nuclear power plants in Sweden is available only in Swedish. However, it was possible to obtain an English translation of a summary report done for the Swedish Nuclear Power Inspectorate on equipment qualification (Ref. 9). Although this report does not provide a complete exposition of all aspects of equipment qualification policy in Sweden, it does give details of some of the more important features of their approach. The report contains a general discussion of environmental qualification, a review of the pertinent conditions that produce environmental stresses, the expected severity of these conditions and the corresponding test requirements.

Discussion of the Swedish regulatory approach to equipment qualification in this section is limited to qualification testing requirements for safety-related equipment located inside containment. In their environmental test requirements, a distinction is made between short-term effects and long-term effects of the environment, under both normal operation and post-accident conditions. Their approach recognizes that there can be local variations in the environmental conditions within the reactor building and these are taken into account in considering the requirement for long-term effects of individual components. For short-term effects, the most severe conditions form the basis of the required test conditions.

4.1 Establishment of Environmental Test Conditions

One of the important first steps in the equipment qualification process is the definition of the conditions under which the equipment must function. This requires a systematic evaluation of many different accident events and the ensuing conditions that can arise. For equipment inside the containment building, the Swedes have used the approach described below.

Plant operating conditions were evaluated for five different modes of operation after the start of plant operation. These were:

(1) Plant Modifications: (Repair, maintenance, clean-up, modification). Here the plant environment is not particularly severe, but there is potential for mechanical stresses (like impact, vibration from drilling into structures being modified or components mounted), wetting, etc.

(2) Normal Operation: Fluctuations in temperature, humidity and ionizing radiation can occur during normal operation which can have a significant bearing on aging of components.

(3) System Failure: This includes minor steam leaks that are too small to initiate dousing, temporary loss of local air cooling, overpressure transients, inadvertent dousing, failures in electrical power and control systems, etc., - i.e. events that cause a short-term increase in environmental stresses.

(4) Moderate Water and Steam Leaks: Included here are small breaks that might initiate dousing at higher temperatures than large breaks.

(5) High Energy Pipe Ruptures: Here dousing action is assumed and components are exposed to severe environmental stresses and possible mechanical stresses.

For each of these modes of plant operation, the degree to which the various environmental parameters - grouped into climatic, mechanical, electrical and chemical - is affected has been assessed in a relative, qualitative manner. This evaluation has then been used as a basis for setting the severity levels for each individual parameter for different modes of operation. These severity levels represent the upper limits of environmental parameters which have a low probability of being exceeded, but do not include any margins. The time for which these maximum levels last depends, of course, on the mode of

plant operation being considered. Environmental test times are selected to give a conservative representation of the exposure to environmental stresses during the equipment's expected mission time.

Selection of the parameter levels discussed above are for the purposes of conducting short-term type tests. For the purposes of aging assessments, environmental stresses during normal operation are used as the basis for testing. The severity levels of temperature, humidity, ionizing radiation and vibration have been selected for different locations within the various nuclear plants in Sweden.

The preceding paragraphs deal with possible environmental conditions after the equipment has been installed in the plant. Cognizance is given to the fact that while equipment can be shown to be functioning properly in a normal environment after transportation, storage and installation, this does not prove that it has not been damaged in some minor way - for example, seals to keep moisture out of a component may have been damaged. To limit the incidence of damage, the environmental conditions for products during transportation and installation are regulated by the enforcement of a Swedish standard on transportation environment.

4.2 Qualification Test Requirements

The methods recommended for type testing under the various environmental conditions are generally the applicable IEC or IEEE standard test methods.

Accelerated thermal aging tests on components with affected materials are based on the Arrhenius criteria.

The required sequence of testing is

- Initial performance verification under normal conditions
- Accelerated aging, where applicable
- Short-term environmental type testing, first with single parameter variation, then with combined parameter test conditions
- Post-accident qualification test
- Final verification

Temperature transients reflecting the various accident conditions are specified for qualification tests.

G. A SUMMARY OF THE LATEST RESEARCH FINDINGS

1. Background

In 1975 the American NRC initiated its own qualification testing evaluation programme at Sandia National Laboratories in Albuquerque, New Mexico. Over the 11 years that this programme was funded, many results relevant to EQ issues were published. The number of technical publications generated during this time is considerable, covering many of the topics related to simulating aging and accident conditions, and to pertinent considerations in equipment qualification testing. In 1985 the NRC set about getting a status report produced of all SNL research work which should also resolve outstanding EQ issues in the NRC programme plan. The end result of this effort was a document NUREG/CR-4301 (SAND-1309) entitled "Status Report on Equipment Qualification Issues Research and Resolution" which was finally published after extensive revisions in January 1987.

This document is a useful compendium of contemporary EQ topics and findings. It covers research work in the U.S.A. as well as in Europe and Japan, and is probably the best single source document for EQ-related research literature currently available. We gathered from talking to people involved in the EQ field in the U.S.A. that in its initial draft form, the findings and recommendations of the report were fairly strong in their condemnation of some of the current practices and positions on EQ issues; views which the NRC staff did not apparently agree with and would not sanction for release and use in their nuclear industry. The tone of the document has been considerably revised during the various stages of peer group review, and in one of the reviewers' opinion, it has lost some of its thrust, although technically it is unflawed. The findings presented in this NUREG/CR-4301 document will nevertheless provide useful information to AECB staff as they refine their position on EQ applications to CANDU plants.

It was known from the outset of this contract that the NUREG document would be published shortly and its content would be most pertinent, however there seemed little benefit in merely including a summary of the findings of that document in this report. It was felt even before the NUREG document was available for our review that its publication would still leave unrevealed or unsettled subtle issues in this complex area. Franklin Research Centre - participants in the peer review of the original NUREG/CR-4301 report - were therefore subcontracted to provide a supplementary interpretation and commentary on the findings of the report. The directive given to FRC was that they should provide a critical commentary on the reports findings and conclusions, in the light of their very extensive qualification testing and research experience. They were asked to write their commentary bearing in mind that not only was the CANDU design and safety philosophy slightly different from the

American reactors, but that the approach to regulation in Canada was not quite the same as in the U.S.A.

The FRC contribution below was written by Mr Gary Toman, Head of the Nuclear Engineering Section, and was reviewed by Dr Sal. Carfagno who has been deeply involved in equipment qualification almost from the outset in the 1960's. He is highly regarded as an expert in this field, having contributed to the formulation of many of the IEEE standards and approaches to qualification testing.

2. Summary and Commentary by Franklin Research Centre

This section provides an overview of NUREG/CR-4301 (Ref. 10) "Status Report on Equipment Qualification Issues Research and Resolution," which is a summary of nearly 100 reports and papers concerning equipment qualification research at Sandia National Laboratories. The report covered three main topics:

(i) Generic issues related to simulating accidents.

(ii) Generic issues related to simulation of aging.

(iii) Special topics related to equipment qualification.

Each discussion of the issues in the NUREG includes findings from Sandia qualification research programs and those from the related U.S. and international programs. Because many of the programs involved testing of specific component configurations and materials, the results often do not lend themselves to definition of generic methodology. In fact, many of the results reported in the NUREG indicate that the planning and performance of a scientifically rigorous qualification program are extremely difficult and costly. Most commercial qualification programs performed as of this writing have included aspects governed by practical considerations and engineering judgement when a scientifically rigorous method was unavailable or proved to be prohibitively costly.

Because the NUREG is an attempt to summarize a large number of research efforts with regard to specific qualification concerns, further summarization herein would not do justice to the report or the work involved. Therefore, highlights will be addressed and a few of the specific issues will be described to show the complexity of the concepts being evaluated. The practical concerns regarding the implementation of some of the recommendations from the Sandia programs are also given.

2.1 Issues Relating to Simulating Accident Conditions

The governing concern in NUREG/CR-4301 for accident condition simulation was "What method of testing properly simulates the conditions that occur in an accident environment?". This concern is heightened by the harshness of the accident conditions for BWRs and PWRs. Most commercial test programs performed to date used sequential radiation and steam testing. Many tests used saturated steam conditions without oxygen in the test chamber. As time progressed, researchers and regulators became concerned that many of the techniques used in testing might not accurately simulate stresses that could lead to equipment deterioration. Questions arose, such as: Does sequential accident stress application cause damage equivalent to simultaneous stress application? Can superheated portions of accident profiles be adequately simulated by saturated steam conditions having the same temperature profile? Do accident dose rates have to be accurately simulated? Must the thermal transient at the outset of an accident be accurately reproduced? Should test chamber environments contain oxygen? Can post-accident periods be accelerated?

Unfortunately, for most of these issues, the research indicated that the results were material dependent and, to some extent, depended upon the adequacy of the definiton of the plant conditions to be simulated.

Also, for some concerns, such as the difference between simultaneous and sequential accident simulations, the results could be affected by the method used to simulate aging. The following subsections describe three of the concerns related to accident simulation in more detail.

2.1.1 Simultaneous/Sequential Accident Simulation

The concern relating to simultaneous and sequential accident simulations is: Does sequential exposure of equipment to radiation and steam environments provide an adequate simulation of the accident, or are synergistic effects important? The bulk of the Sandia research described relates to testing of cables with ethylene propylene rubber (EPR), cross-linked polyolefin (XLPO), Tefzel (Trademark E.I. Dupont), and chlorosulfonated polyethylene (CSPE) materials. The results of a number of tests performed in differing manners are described. The basic findings were that the importance of synergistic effects (i.e. significantly different levels of deterioration when components are exposed to simultaneous stresses as compared to a series of stresses) in accident simulation depends upon

(i) the type of material tested
(ii) the presence of oxygen during accident simulation
(iii) the preconditioning of the test specimen

Many materials exhibited no significant synergistic effects during simultaneous exposure when compared to the results of sequential tests. One complicating factor in evaluating simultaneous versus sequential accident simulation is the fact that different methods of preconditioning (aging simulation) can affect accident simulation synergisms in certain materials. Although the materials evaluated by Sandia indicated that the choice of a specific aging simulation method can cause the result of simultaneous and sequential accident simulation tests to be equally severe, unfortunately the affected materials each required a specific preconditioning method. In other words, no generic method for aging simulation eliminated all of the synergistic effects during accident simulation. Moreover, different manufacturers' materials, having the same generic description, required different age preconditioning techniques to eliminate accident simulation synergisms. Therefore, to eliminate accident simulation synergisms, screening research programs would be necessary for each specific material.

For some materials, another complication in simultaneous versus sequential test evaluation is the presence of oxygen in the test chamber during accident simulation. Sandia found that the least deterioration occurred for two EPR materials when they were exposed to sequential accident simulation without air in the test chamber. When air was included in the test chamber, sequential testing yielded results similar to simultaneous accident testing with oxygen, provided the appropriate aging simulation sequence was used.

The application of these research findings to qualification testing is not particularly easy. Currently, sequential exposure is the only commercially available means of simulating accident conditions; no commercial facility offers simultaneous steam and radiation exposure. The application of specific aging methodologies for specific materials in conjunction with sequential accident testing is complicated. The most appropriate aging method (e.g. irradiation aging before thermal aging, irradiation aging at a specific elevated temperature before thermal aging, thermal aging before irradiation) must be known for the organic materials in use. A relatively small number of compounds have been tested by Sandia. The reports for these materials generally described them by their generic names only. Therefore, insufficient information is available to choose the appropriate aging methods without performing special tests prior to a qualification program. Equipment containing a number of types of organic materials would further complicate the choice of the aging simulation method. Tailoring of aging methodology to mitigate the need for conducting simultaneous

accident simulation is applicable to equipment that has only one organic material, or that has only one organic material that is significant with respect to loss of safety function.

One practical method of eliminating this possible need for simultaneous accident simulation is the inclusion of air in the accident test chamber. The choice of an appropriate partial pressure of air is a problem because the parameter has not been defined for most accident environments. Introduction of air into the chamber may also be limited to post-accident portions (a few hours to a few days into the simulation of the test profile), because oxygen is generally swept from the test chamber during the initial transient and then removed in dissolved form in the condensate from the chamber. After the test profile returns to a high humidity, non-pressurized condition air can be added to the simulated environment.

2.1.2 Superheated vs Saturated Steam Effects

Initial portions of the accident profiles for most plants have superheated steam conditions. In some cases, qualification tests have been performed with saturated steam conditions, and in others with portions of the profile having superheated conditions and the remainder of the profile having saturated steam conditions. The question under study by Sandia was: For the same temperature profile, is duplication of the superheated condition necessary or can a saturated condition be used? One Sandia conclusion was that functional capability for some components may be lost when superheated conditions are followed by saturated conditions during which moisture condenses in and on the component. Significant deterioration of electrical insulation may not be apparent during the dry superheated conditions, but would be observable during moist saturated steam conditions. It should be noted that saturated conditions do occur at some point in nearly all LOCA profiles. Some research also indicated that equipment closed in a housing will have slow temperature responses with respect to the superheated steam profile, showing that accurate simulation of rapid rise thermal transients may not be critical.

The duplication of superheated profiles is preferred, provided that the portion of the profile in which high moisture conditions occur is appropriately simulated in the test. For some equipment, testing at saturated conditions for the entire profile is significantly more severe due to the pressures being higher than those associated with superheated steam.

2.1.3 Effects of Oxygen during Accident Simulation

Although it is recognized that oxygen or air content inside of containment during and following an accident is not well defined, there is a concern that inclusion of only steam in the test chamber will not yield conservative results, because no oxygen is available for oxidation reactions in the materials under test. The tests performed by Sandia indicated that some materials degraded more rapidly under accident conditions with increased levels of oxygen, whereas polyvinyl chloride degraded more when oxygen was decreased. Therefore, the effects of oxygen inclusion in a test chamber are material specific and can be significant. Lack of oxygen in the test chamber may be inappropriately favourable to some materials and unfair to others. One Sandia program showed that two commerical EPR insulations had a larger reduction in tensile elongation properties when subjected to a LOCA simulation with oxygen present than without oxygen. Tefzel (Trademark E.I. Dupont) was also found to be more degraded when oxygen was present in the LOCA simulations; however, the amount of degradation depended on the age conditioning methodology. Oxygen in the LOCA chamber was not important for the chlorosulfonated polyethylene (CSPE) and chlorinated polyethylene samples tests. Most current qualification programs do include air in the test chamber during post-accident period simulations since air is expected to be present in most containments following an accident.

2.2 Issues related to simulation of Aging

Sandia's efforts related to simulation of natural aging centered on the appropriateness of acceleration methodology, the significance of differing aging techniques, and the means of evaluating changes in material parameters caused by aging. The appropriateness of the use of the Arrhenius model was evaluated for thermal aging. Dose-rate effects, sequential versus simultaneous aging, mechanical stress simulation, and the effects of oxygen and humidity on the simulation were studied. Although the results of some of these studies have practical application in qualification programs, the results of other studies are applicable mainly to further qualification research programs. The following subsections provide examples of each.

Oxygen diffusion was of concern in many of the Sandia aging evaluations. At high acceleration rates during simulation of aging, oxygen has insufficient time to diffuse into the material to replace the oxygen consumed in the chemical reaction associated with aging. Therefore, non-homogeneous aging, which is not representative of natural aging, occurs across the thickness of the material. For example, the edges of the material may harden while the interior remains nearly

unaffected. Sandia developed special techniques to profile differences in density and hardness across the thickness of material samples.

The recommendations from the Sandia aging evaluation programs were mostly related to further research in material property evaluation and determination of more precise activation energies. The recommendations included development of activation energies from longer term, lower temperature testing; evaluation of diffusion-limited oxidation effects prior to application of the Arrhenius thermal model; and use of material profiling techniques to determine if non-Arrhenius behaviour was occurring during aging simulations.

2.2.1 Limitations of the Arrhenius Method

The NUREG describes the limitations of the Arrhenius method and the means for overcoming them. One concern is that activation energies for some materials change over the large temperature range between natural and acceleration temperatures. The activation energy is often determined at temperatures between 120 and 150 C. The natural aging temperature is most often between 30 and 60 C. The predominant chemical reactions may be different in these two temperature ranges. Therefore, for some materials, the accelerated aging may be non-representative of the normal aging process.

In other materials, two or more degradation mechanisms having different activation energies may be competing. An example is given for an EPR insulation that has a thermal oxidation mechanism, and a copper-catalyzed oxidation reaction (copper form the conductors) that causes a high level of degradation near the conductor. A key concern with high rate Arrhenius acceleration of thermal aging is the effect of diffusion-limited oxidation effects. The effects of high rate acceleration can be reduced by performing the simulation at lower temperatures. However, the length of the simulation increases rapidly as temperature is reduced, causing both schedule and cost concerns to require limiting the reduction in the acceleration.

2.2.2 Dose-Rate Effects

The NUREG concern was: Do different radiation dose rates cause differing levels of degradation for a given dose and, if so, how should dose-rate be simulated? Earlier work indicated that the equal dose/equal damage model was valid. However, most of these findings were based on higher dose rates than would occur during

normal operation of nuclear power plants. The work performed by Sandia at lower dose rates produced strong evidence that dose-rate effects are a definite factor in aging simulations of polymer materials. They found that dose-rate effects always involve oxidation mechanisms. However, oxidation reactions that occur during actual plant conditions may not occur during rapid simulations, therefore, material specimens subjected to high dose-rate radiation exposure may display properties that are not representative of real-time exposures. The significance of the dose-rate effects in various materials ranged from large to insignificant, depending upon factors such as polymer type, aging conditions, sample geometry and degradation parameter being monitored.

Sandia found that two general classes of dose-rate effects exist; a well-known physical effect, involving oxygen-diffusion-limited degradation, and a chemical effect, involving a rate-determining chemical reaction. Oxygen-diffusion limited degradation causes non-homogeneous aging, causing properties such as elongation-at-break appear to be much higher for specimens subjected to high dose rates than for those subjected to low dose rates. When chemical dose-rate effects are present, accelerated aging simulations become more complex, as this usually implies that both synergistic effects (low-temperature radiation plus elevated thermal environments), and sequential ordering effects will exist.

Sandia has developed and tested a general kinetic model for treating chemical effects, synergistic effects and ordering effects arising from peroxide breakdown. Their model shows that there are two types of limits for these dose rate effects: depending on kinetic constants, the dose-rate effects may either disappear on going progressively to lower dose rates, or remain very strong. Thus careful consideration should be given to the application of dose margin in the simulation of radiation aging effects.

For practical qualification purposes, the dose rate for radiation aging should be as low as can be accommodated within a reasonable cost and schedule if the susceptibility of the material to dose-rate effects is unknown. Dose rates between 10 and 100 krad/h can generally be accommodated during an aging simulation, and will produce much more representative deterioration than the 1 Mrad/h dose rates that have often been used.

The Sandia work also included a brief survey of research on dose-rate effects on electronic components. Numerous studies suggest that electronics are sensitive to radiation damage, and several world-wide research programmes may produce useful data in this area in the future. On this topic, the NUREG report is

brief, stating that operational temperature and long-term radiation effects have not been investigated, and recommending that caution be exercised when evaluating aging phenomena in semiconductor devices. It suggests that consideration be given to combining neutron and gamma radiation environments in simulating radiation effects on electronic components.

2.2.3 Simultaneous vs Sequential Aging Exposures

The concern addressed in the NUREG is: Can sequential aging be used to adequately simulate simultaneous thermal and radiation environments and, if so, does the order of the sequence matter?

The Sandia research indicated that for many organic materials, sequential exposure (radiation followed by thermal exposure, and thermal followed by radiation) is similar to their response to combined radiation and thermal exposure. However, for some materials, such as polyethylene and polyvinyl chloride, radiation followed by thermal exposure usually led to much more severe deterioration, more closely matching the deterioration produced by simultaneous exposure. The conclusion was that, for conservatism, radiation aging should precede thermal aging.

In commercial qualification, facilities for simultaneous radiation and thermal exposure are not readily available. Most often, qualification laboratories place subcontracts with radiation laboratories, and practical concerns often govern the test procedure. Common practice has been to irradiate test specimens to a combined accident and aging dose after thermal aging but before seismic testing. Compared to a sequence of radiation aging, thermal aging, seismic test, and accident irradiation, time is saved because the specimens do not have to be taken to the radiation laboratory twice. Also, the specimens are not subjected to double handling during which they may be damaged.

2.2.4 Humidity Effects

The concern of the research was: Does humidity affect aging and, if so, how can humidity aging be accelerated? The finding of the research was that humidity effects do not appear to be of major importance in radiation environments, provided that the material is known to have humidity resistance in thermal environments (i.e. if a material is humidity resistant in thermal environments, it should be humidity resistant in radiation environments). The Sandia research indicated that selection of humidity-resistant materials is important.

Sandia found that the Arrhenius model could be used for humidity aging in thermal environments. However, application of this result is not readily usable because activation energies relevant to humidity environments are not available for most materials. An interesting finding reported in this segment of the NUREG is that Kapton (Trademark E.I. DuPont), while having excellent thermal properties, is sensitive to humidity and suffers hydrolytic degradation that renders it weak and brittle when subjected to high humidity environment for long durations.

2.3 Special Topics related to Equipment Qualification

This segment of the NUREG report describes qualification-related issues such as different approaches to qualification testing, results from Three Mile Island Unit 2 equipment evaluations, criteria for selection of simulation methods, and radiation damage thresholds. The following describes some of the salient issues.

2.3.1 Multiple Sample, Fragility and Overstress Testing

Current EQ practice is based on type testing (i.e. normally test one sample specimen), with margins incorporated to account for possible variations in equipment manufacture. It has been suggested that multiple sample tests could complement type testing by giving a broader safety perspective; and fragility tests (testing to the point where it can no longer perform its function) and overstress (increased total stress) test methods could help identify failure modes and failure thresholds.

These three approaches were evaluated by Sandia on a limited basis to determine whether approaches different from those currently used in qualification programs could be used to gain a broader safety perspective. When considering qualification results, questions always exist, such as: Did the component just barely pass the qualification test or was there a large capability left after the accident simulation? Was the device the best one ever produced, or was it really representative of the remainder of the population? Multisample, fragility, and overstress testing could each be used in response to these questions. Sandia evaluated overstress testing for radiation effects and concluded that, if high dose-rate overstress doses were used, poor materials with large dose-rate effects could be selected over better materials with small dose-rate effects. For some materials, overstressing with radiation may cause improved capabilities at high doses by comparison to exposure to the required dose. Sandia's conclusion was that use of a high overstress dose does not compensate for dose-rate effects.

Fragility testing was analyzed on the basis of a series of seismic tests on lead acid batteries. The g-levels of tests were increased in successive tests. The tests revealed the level of margin between the needed capability and the capability at failure, and provided insight into the failure mechanism from overstress. It was not clear that the failure mechanism from overstress conditions related to the mechanism that would apply to expected conditions. One particular drawback to fragility testing is that failure will occur. Failures have connotative value, no matter if they occur under much higher levels of stress than could be expected in actual applications.

For practical qualification purposes, limited overstressing has been used in the form of margins which are added to test parameters to account for manufacturing variations and uncertainties in the qualification process. The general practice has been to limit overstressing wherever possible to provide a higher probability of successful qualification.

Multisample testing was evaluated by subjecting different samples to different conditions and by having multiple samples subjected to the same test program. In one test, an unaged transmitter was found to be subject to large changes in accuracy during thermal transients while aged transmitters were not. Aging of the transmitter actually improved its capability to resist thermal transients. Review of results from multisample tests of cable indicated that some insight into random success and failure phenomena may be possible but not on a statistical basis.

Multisample testing to identical qualification sequences has been performed in some commercial qualification programs. However, it has been limited mostly to small devices due to cost and test chamber size limitations. The number of specimens has generally been small and did not yield statistical data relating to ability to withstand an accident environment.

Accident testing of aged and new components is required only by the IEEE standard for cables. A concern existed that unaged cable could be more vulnerable to accident conditions than is aged cable.

Fragility testing can be used only for a specific type of test and not for the full qualification sequence. Testing the same component to successively harsher seismic and LOCA environments is impractical. For LOCA conditions, testing separate samples to successively more severe LOCA environments would be extremely expensive.

2.3.2 TMI-2 Experiences

The evaluations of equipment removed from TMI-2 after the 1979 accident provided insight into many areas relating to qualification. For instance, evaluation of terminal blocks from TMI-2, and those tested under similar environments, indicated that surface conditions (dirt, moisture, and contamination) were most important in leading to failure and that mounting and housings are also critical. Most U.S. plants have now chosen to eliminate terminal blocks inside containment and have substituted butt splices with heat shrink tubing.

The TMI-2 equipment evaluations also found that moisture intrusion into equipment such as pressure transmitters was common and that 24% of the tested in-containment cables (233 total) had circuits classified as inoperable.

2.3.3 Evaluation of qualification for cables

The Sandia study evaluated the qualifications procedure given in IEEE Standard 383-1974 for cable to determine if it was adequate. Simultaneous applications of environments were compared to sequential ones, and differing cable specimens were compared. Key findings of the study were:

1. Qualification by generic material type is not possible for cable jacket and insulation materials. Different formulations of the same generic material, such as EPR, responded differently to test conditions.

2. For some types of cables (i.e. some EPR-insulated cables), qualification test results for individual conductors are not adequate for multiconductor cable qualifications. Jacket and insulation interactions resulted in specimen failure for a certain multiconductor EPR-insulated cable. The study recommended testing single and multiple conductor EPR cables. Cross-linked polyolefin cables were not found to be subject to jacket-insulation interactions that lead to failure during design basis accident simulation.

3. The minimum bend radius in the qualification test accident simulation should represent the minimum bend radius of the installed condition. Most commercial tests have not simulated the minimum installed radius. For low voltage cable, the minimum bend radius for installation may be as little as four times the diameter of the cable, whereas the bend radius for LOCA tests is frequently 20 or more times

the cable diameter.

2.4 Conclusions

The Sandia work provides valuable insight into qualification-related issues. Some of the results and recommendations can be readily transferred to commercial qualification efforts. Others are more related to future qualification research efforts or must be tempered by practical testing limitations.

H. EQUIPMENT QUALIFICATION IN CANADA

1. Present Status

The qualification of safety-related equipment for assured operation in abnormal and accident environments has from the outset been implicit in the CANDU safety philosophy. The fundamental requirement is to have the capability to perform the three basic safety functions (shutdown, cool and contain) engineered into the design. The fact that some, if not all of these safety functions, must be carried out after the occurrence of the initiating event, implies that the equipment and services required must be immune to any ensuing environmental conditions. It is also implicit that this capability be preserved throughout the operating life of the plant.

In Canada, the regulatory concept has been for the designers of the nuclear plants and the utilities to be responsible for all aspects of the design, construction and operation, and for the regulators to perform an independent check that the basic safety requirements are complied with. It was implicit that the special safety systems and associated auxiliary systems be designed to function as required under the relevant conditions. However, it was not until the publication of Consultative Documents C-7, C-8 and C-9 that general regulatory requirements for environmental qualification of equipment in the special safety systems were formally stated.

The basic environmental qualification requirements for safety-related equipment in CANDU plants are laid out in plant-specific Safety Design Guides. These documents define only in broad terms the EQ requirements (both environmental and seismic) and identify the safety-related systems to which these apply. As these design guides have had to be produced for use by the system designers early in the design phase, usually long before all of the design details and accident analyses have been

finalized, they have been subject to change as the projects have proceeded. To notify designers of changes in the design guides, the practice has been to issue design guide supplements, as required. Also, near the final stage of design and construction prior to application for an operating licence, a systematic review has normally been done by AECL and the utilities Ontario Hydro, Hydro Quebec and New Brunswick Power to check that all the required measures have been implemented.

The earlier safety design guides generally adopted a 'worst-case' approach in defining the accident environment for qualifying safety-related electrical equipment, and instrumentation and control equipment. Later design guides included the consideration of lesser accident scenarios (small LOCA/steam main break), but only one temperature transient of a representative point within the reactor building following a large LOCA was proposed as the qualifying condition. This profile was said to be also representative of the environmental transient that would follow a large steam main rupture. As the design guides have stated a preference for qualification by type testing, a test chamber temperature profile was devised to assist the designers in applying the reactor building temperature transient. This test chamber temperature profile was considered to "encompass all the physical situations" that would arise in the reactor building from the release of mass and energy following the postulated initiating event - i.e. the peak values, the rates of change of temperature and the amplitude and frequency of the cycling due to the operation of the dousing system and the large local air coolers.

It is perhaps pertinent, or at least enlightening, to point out here that the temperature transients used for qualification testing in Canadian nuclear power plants are far less severe than those for the American pressurized water reactors. To illustrate this point, Figure H-1 shows the temperature transient for 600 MW CANDU qualification testing superimposed on a typical LOCA/HELB temperature profile for a PWR in-containment environment simulation taken from Appendix A of IEEE-323-74.

Values of ambient pressure during the application of the temperature transient are specified in the design guides. Regarding humidity, saturated conditions are to be applied throughout. These conditions and the times denoted in the temperature profiles define the environment to be applied in type-testing qualification. For each safety-related system identified in the design guides, the duration of the required test was defined - either 'short-term' (i.e. 3 min), or 'long term' (i.e. the initial 30 min. transient followed by six hours at steady post-LOCA conditions). One other category - 'brief term' - was used in a Pickering 'B' design guide supplement in

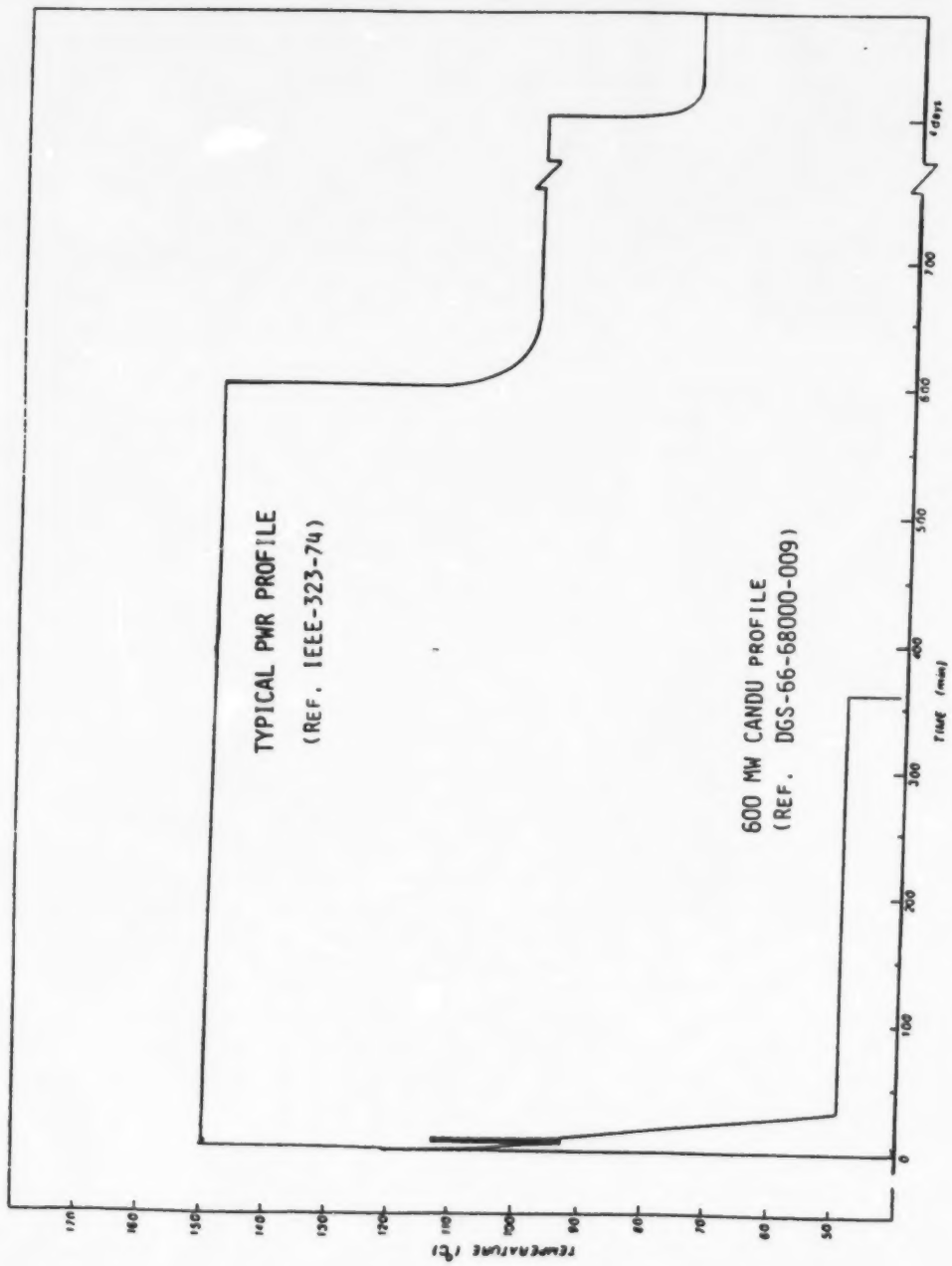

FIGURE H-1: TEST CHAMBER TEMPERATURE PROFILES FOR CANDU 600 AND TYPICAL PWR LOCA/HELB SIMULATIONS

referring to some of the short-term reactor regulating system functions following a small LOCA or steam main break. This latter category however has no bearing on the qualification testing required, as the degree of qualification needed to cover a small LOCA or small steam line break is more arduous, being identified as 'short-term'.

The effects of radiation are catered for in the safety design guides only in so far as an exposure of 100 kGy (10 Mrad) is recommended as a limiting total dose. This figure is the sum of the assumed 30 year lifetime dose 30 kGy (3 Mrad) for normal operating conditions and an accident dose of 70 kGy (7 Mrad). Equipment identified for short-term qualification need only be subjected to a normal operating dose, to be determined by the designer.

Thus the safety design guides, rather like some of the early American EQ standards, provide the designers a framework to use for equipment qualification. General guidelines for ambient temperature, humidity, radiation (inside the reactor vault) and pressure are given, but many of the details needed to define the normal environmental and operating conditions are left up to the individual designers to specify. The onus for the correct interpretation, implementation and documentation of EQ requirements has rested almost entirely upon the individual system designers.

The implementation of measures to comply rigorously with the above-mentioned qualification requirements has developed in a different manner to other countries where regulatory requirements have been the driving force. The limited degree to which the various aspects of EQ have been addressed in completed CANDU plants to date could be said to derive from the nature of the safety design guides. While they have specified the general concept, and correctly have not presumed to dictate to the individual system designers how to go about implementing the requirements, many of the pertinent issues in contemporary EQ programmes have been omitted from the guides. The American standard IEEE-323, which might have been used at least as a basis for identifying some of these issues, was referenced only in a secondary way -i.e. to act as a guide to the designer if he was unable to qualify any of his equipment by the preferred method of type-testing. Thus although it has been asserted that the intent of the safety design guides was concurrent with that of the of IEEE-323, this has been true only in the most general sense. Significant factors such as aging, qualified life, synergism, sequence of testing, margins were not even mentioned before Darlington. This is difficult to explain, as some of the earlier design guides, e.g. for Pickering 'B', Bruce 'B' and the 600MW plants, were written in the late 1970's and early 1980's when these issues were already well known within the nuclear industry and had been addressed in IEEE-323 and other

standards. A review of the latest safety design guides does however indicate that the attitude of CANDU designers is evolving towards a more rigorous approach to EQ in future plants.

Although the safety design guides prior to Darlington, may not have addressed some of the controversial issues that have been tackled in the U.S.A. over the past 15 years, they nevertheless have incorporated some good concepts. The DG-68000-003 guides emphasize the importance of recognizing that the overall goal is to maintain the capability of performing the basic safety functions, implying that the qualification of individual pieces of equipment should be done to assure system operation and not merely individual component function. The guides have retained a generality which makes it a requirement that all equipment types - electrical, electro-mechanical and mechanical - needed to execute the safety functions are to be qualified, and not only the electrical equipment, as in other countries.

As for the implementation of these requirements, an audit of the EQ documentation and in-service maintenance/surveillance measures would be necessary to formulate an accurate assessment. This has not been done within the scope of this project, but having been involved in qualification-related work for a number of years and having had numerous discussions with colleagues in this field during the course of this project, some general statements can be made. The implementation of the EQ requirements in the design and construction of operating CANDU plants to date appears to have followed the direction given in the safety design guides. Without any existing Canadian EQ standards, apart from seismic qualification, and without any substitute standards having been adopted, qualification efforts have been compliant with the design guide specifications. Where these have been non-specific, or have excluded age-related considerations for example, such shortcomings will have been reflected in the applied EQ measures. Type testing has been the preferred method and qualification reports documenting the essentials of the testing done have been generated. The absence of a rigorous on-going EQ process in Canadian plants, like that required in other Western countries, must in part be due to the lack of pressure to do any more than has been deemed sufficient.

2. Recommendations for New (future) CANDU NPP's

2.1 Recommendations on EQ Standards and Requirements

In each of the countries surveyed, there is in effect a general, but definite, regulatory requirement regarding the qualification of safety-related equipment. In addition there exists a family of industry standards, endorsed by the regulatory body, that prescribe the methodology for qualifying various types of equipment. The Canadian equivalent has a less formal format, and as a starting point to establish a more structured basis, the following recommendations are made:

(1) (i) Prepare a Regulatory Guide that defines the overall requirements for qualifying electrical and mechanical equipment important to safety for new CANDU plants.

Although the proposed regulatory guides C-7, C-8 and C-9 include broad requirements for qualification for the special safety systems, there should be an umbrella document that lays out the general EQ requirements for all safety-related equipment.

(1) (ii) The scope of this guide would be to set the basic requirements of each part of the EQ Process.

In the U.S.A., the development of the regulatory position has gone along with the evolution of the IEEE standards, and effectively has endorsed the standard and merely added exceptions or additional requirements. Without any equivalent Canadian standards on EQ, the regulatory guide should either endorse the IEEE 'mother' standard (IEEE-323) or IEC-780, along with appropriate exceptions or extensions, thereby formally establishing a framework of the EQ process in future CANDU NPP's. This guide would define the overall requirements in each phase of the EQ process, and set basic policies on critical aspects of the EQ programmes discussed in the main body of this report. This guide should pertain to electrical equipment at least, and preferably include mechanical equipment.

(2) Encourage the development of a series of CSA standards that set down the details of qualification methodology pertinent to the CANDU design for the various equipment types.

The standards of the various countries surveyed are not identical but seem to be based upon the IEEE standards, which is understandable as the plants to which the standards apply are based upon American designs. The CSA standards would also be similar to the IEEE standards to the extent that the generic topics covered and the qualification procedures recommended would be essentially the same, but CANDU-specific features would

be incorporated. These standards should reflect the latest findings of Canadian and international research into the many issues of EQ already discussed.

The application of EQ programmes and their assessment need to have technical bases that are justifiable from current experience and research work, and indeed the EQ standards are founded upon technical bases. However issues constantly arise in the assessment of EQ submissions done according to the most recent methods, and also in assessments of EQ submissions on equipment qualified initially with less rigour and having been in service for some time. Examples of some such issues raised by the NRC and the ensuing research effort to provide answers were discussed in Section G. Having performed a survey of standards, practices and research results, the following recommendations are made towards consolidating the technical basis for assessing future EQ submissions in CANDU nuclear power plants.

(3) Until the CSA publishes CANDU-specific EQ standards, qualification done according to the methods specified in the IEEE standards should be acceptable.

It is clear that in qualification type testing, the simulated accident transients should reflect CANDU conditions - i.e. LOCA, HELB.

(4) It is recommended that there be a requirement for EQ submissions to be accompanied by an organized plan for maintaining control of the qualified configuration and that this plan have some means by which its execution can be audited.

Proposed measures to preserve EQ status should be an integral part of maintenance programs so that there is a definite procedure for procuring, storing and installing spare parts of qualified safety-related equipment that is consistent with quality assurance requirements. When there are upgrades or changes in the spare parts, the impact of these on the EQ status should be evaluated and recorded. All of this is of limited value unless the equipment is verified as being in a condition consistent with the EQ test conditions, especially paying attention to the interfaces, and that the maintenance/surveillance plan is actually seen to be implemented.

(5) The use of recognized data bases in the preparation and evaluation of EQ submissions should be adopted.

There are material data bases and component data bases, the material data bases being more versatile and reliable than the component data bases. These are an important source for checking or establishing the activation energy of materials, which can range from 0.7 to 1.8. The main data bases are the System 1000 by Digital Engineering, and the Wylie materials data base. EPRI has created a component data base EQDB which is maintained by NUS Corporation.

2.2 Recommendations on Applications of EQ Standards and Requirements

Although the Sandia National Laboratory staff were asked to determine the adequacy of the IEEE standards in qualifying electrical equipment, their research report discussed in Section G does not furnish a direct response. Extractions from their report lead to the following cautionary notes related to the application of EQ standards and requirements.

(1) Do not accept without question EQ submissions on electrical cables done in accordance with IEEE standard 383-74.

This standard specifies that sequence testing is an acceptable method for simulating accident conditions. Research shows that generally there are no accident synergistic effects, but they can show up in some materials, so test conditions should correspond closely to actual use conditions. Tests on single conductor cable are not always representative of multiconductor cable of the same material.

(2) Wherever possible, the use of terminal blocks in safety-related instrumentation circuitry should be avoided in potentially wet/damp environments.

The formation of surface moisture films cause low level leakage currents during humid conditions that effect the functioning of the connected circuits. Most industry standards do not require monitoring of these leakage currents during LOCA testing.

(3) Accelerated thermal aging by Arrhenius methodology is generally acceptable provided that testing times are not less that 100 h, and the activation energies applied are verifiable in one of the recognised materials data bases.

Research results reported by Sandia indicate that although some materials exhibit non-Arrhenius behaviour and diffusion-limited oxidation effects are important, this methodology is acceptable especially if long-term testing is applied. However, there is abundant evidence in the literature that the results of accelerated aging tests can be misleading. The French experience with aging tests of solenoid valves is illustrative. Specific component materials were selected to withstand the thermal aging temperature (120 C), but in combination with the heat dissipated in the coils, the actual temperatures were too high for the seal materials. The test sequence was revised to give more emphasis on the cyclic operation of the valves, but the material selected on the basis of thermal aging requirements was not as effective for the cyclic operation. Their approach is now to give more emphasis on operational aging (i.e. number of cycles) rather than thermal (Ref. 4, p242).

(4) Where there is uncertainty about the applicability of thermal aging data to a particular formulation of organic material being used in some safety-related equipment (and this is frequently not known for it might be proprietary), then a recommended approach is to apply conservative values for activation energy and operating conditions to deduce a conservative life, and combine this with a surveillance/replacement plan.

This situation may arise frequently, for even though many preconditioning tests have been done, and there is much information around, it is not always a straightforward matter applying published test data. There are many variations in the formulations of organic insulation materials, which are often combined with different filler materials, and it is frequently not possible to determine from test reports the precise formulation of the material types that have been tested. Futhermore, the component manufacturers may not have tight control on the production of the feedstock organic materials they use in manufacturing their equipment, and it is quite possible that slight variations in formulations go unnoticed. Therefore some conservatism in the application of data is recommended to minimize such uncertainties.

(5) As dose rate effects are important in radiation preconditioning, there should be some indication that they have been taken into account in the qualification of equipment that contains polymer insulation, sheathing or sealing materials.

(6) Preconditioning by sequential exposure to aging parameters is generally a satisfactory approach, preferably applying the radiation before thermal aging.

Investigations into sequential versus simultaneous simulations both of accelerated aging and accident conditions, generally indicate that sequential simulations produce the same or at least conservative results. This is fortunate for there are not many facilities that can perform simultaneous simulations. Generally radiation aging should be done before thermal aging, but where the polymerization of the material can be affected by exposure to high dose rates, this should be taken into account in the submission.

(7) The presence of oxygen (i.e. air) in the steam during LOCA simulation tests may be very important for equipment or material degradation.

3. Recommendations for Currently Operational CANDU NPP's

The following recommendations related to currently operational plants are offered:

(1) A review of all qualification test reports on un-aged specimens should be carried out to identify equipment containing materials that are known to be prone to significant degradation due to thermal and radiation aging.

(2) A qualified life should be established for equipment that is identified as containing materials that exhibit aging degradation tendencies, using the Arrhenius model for thermal effects and current data for radiation effects. Maintenance plans should be seen to be initiated or revised so that the specific aging characteristics are taken into account. This requires that there also be a surveillance/replacement plan in place through which age-related degradation might be identified and components replaced when necessary.

Where qualified equipment has to be replaced, it should be done with equipment qualified in accordance with current EQ practices and standards.

I. RECOMMENDED FOLLOW-UP WORK

The EQ practices of the Japanese nuclear industry have not been included in this report. They have an established EQ policy and have been major contributors to the international research effort for some years. It would be worth examining their policies, standards and regulations to compare them with other nation's EQ processes and to investigate their applicability to CANDU NPP's.

There is still a great deal of research work that needs to be done towards developing effective qualification methods and practical degradation monitoring techniques. The research programmes being promoted by the AECB Regulatory Research Branch on assessing NPP aging and maintenance programmes, and their intention to make full use of research results are a positive move in the right direction. The anticipated prolonged shutdown of Pickering A NPP generating units during the pressure tube replacement programme seems a good opportunity to gather good information pertinent to the Canadian EQ effort.

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